AQUIFER EXEMPTION MANUAL

PRELIMINARY REPORT

FOR

USEPA REGION IX

UNDER CONTRACT NO.

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Respectfully Submitted

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CHAPTER I

INTRODUCTION

Purpose of Aquifer Exemption Manual

The Underground Injection Control (UIC) Programs are designed to prevent underground injection through wells which may endanger drinking water sources. A fundamental requirement of the UIC regulations, is that all underground sources of drinking water (USDW's) be protected except in cases where an exemption is allowed. The UIC regulations specify administrative guidelines (40 CFR Sec. 144.7) and technical and economic criteria (40 CFR Sec. 146.4) for the exemption of aquifers or portions thereof from classification as USDW's.

The UIC regulations however, do not specify how these exemption criteria are to be applied. The Aquifer Exemption Manual specifies technical and economic criteria and presents guidelines to ensure that aquifer exemption requests will be reviewed under consistent procedures.

The manual is broadly applicable to all classes of injection wells, although some aspects will apply strictly only to a particular class of injection wells. The intent of the manual is to provide basic guidelines to the regulatory personnel in the initial screening of aquifer exemption requests. The various engineering, hydrogeologic and economic factors that have to be considered in an aquifer exemption request, will remain as an integral and important part in the aquifer exemption decision process. These factors are also presented and discussed in the manual.

Scope of Aquifer Exemption Manual

This manual summarizes the geologic, hydrologic, engineering and economic factors that have to be considered in evaluating an aquifer exemption application for wastewater injection operations. Procedures for determining the radius of migration of the injected fluids away from the injection well bore within an aquifer, and for determining the adequacy of the confining strata to contain the injected wastewater are included in the manual. The methodology to determine costs to develop the proposed exempted aquifer as a water supply source and costs to develop alternative water supplies are also presented. Guidelines to ensure that aquifer exemption requests will be reviewed under consistent procedures are presented. Also, essential and important parameters that must be considered in an aquifer exemption evaluation have been highlighted, in order to aid regulatory personnel in the decision-making process.

A suggested checklist of all data elements and factors that have to be considered in an aquifer exemption evaluation has also been developed.

CHAPTER II

GUIDELINES FOR APPLICATION OF AQUIFER EXEMPTION CRITERIA

Application of the aquifer exemption criteria outlined in the UIC regulations to specific projects is hindered because they are highly subjective and difficult to evaluate in terms of long time frames associated with groundwater management programs. The guidelines presented in this chapter along with material contained in this manual will aid in ensuring that aquifer exemption requests will be reviewed under consistent procedures, and will aid regulatory personnel in the decision-making process.

The guidelines presented here should generally be applicable to all types of injection wells. However, since every project facility will have its own unique characteristics, every aquifer exemption request will have to be evaluated on an individual basis, so that all important site-specific factors are taken into consideration.

1. The total dissolved solids (TDS) of the subsurface fluids in the proposed exempted aquifer is a critical parameter in an aquifer exemption evaluation. Any aquifer with a salinity of less than 10,000 mg/l total dissolved solids is defined as an underground source of drinking water (USDW) (40 CFR Sec. 146.3) and therefore must be protected under the UIC regulations. Generally water used for drinking purposes contains TDS of less than 3000 mg/l. However there are some aquifers, both surface aquifers and deep, confined aquifers

that contain groundwater in the range of 8,000 to 10,000 mg/l, thus meeting the definition of a USDW.

Surface aquifers lack a subsurface confining layer to contain the injected waste. In addition, surface aquifers are widely used for drinking water, so that even if a particular area is contaminated or unused, other areas hydrologically connected are likely to be used or usable. Therefore, even though some surface aquifers may have TDS in the range of 3,000 - 10,000 mg/l and satisfy the criteria for exemption in CFR Sec. 146.4, it is recommended that exemption be denied for waste injection into surface aquifers for the reasons mentioned earlier.

Deep, confined aquifers that contain groundwater in the range 8,000 to 10,000 mg/l of TDS could qualify for exemption if the exemption criteria stipulated in 40 CFR Sec. 146.4 are met. However, each aquifer exemption request will have to be evaluated closely on a case by case basis before exemption can be granted or denied. Hazardous waste and radioactive waste disposal applications will especially need to be scrutinized and evaluated very closely.

2. The adequacy of the confining interval in preventing vertical migration of injected wastes into an overlying USDW is also an important criterion in evaluating an aquifer exemption request. The general geological characteristics of an acceptable confining interval are:

(i) Sufficient thickness, lateral extent and impermeability to confine waste to the injection interval.

(ii) The absence of faults or extensive joints or fractures that would permit escape of injected wastewater from the injection interval into adjacent aquifers.

Additionally, confining intervals must not be breached by improperly plugged wells or by induced hydraulic fractures that would permit the vertical escape of wastewater into adjacent aquifers.

Most states at the present time do not have set standards regarding the thickness of the confining layer. Each case is evaluated on an individual basis, and the adequacy of the confining interval determined after an evaluation of all the available engineering and geologic data. However, in some states such as Oklahoma a minimum thickness of 500 feet is required for injection rates about 1000 barrels per day, and a minimum thickness of 200 feet for injection rates below 1000 barrels per day. Although, thickness of the confining interval is a critical parameter, other parameters such as the lithology of the confining interval, its lateral extent and continuity, its impermeability, injection rates and injection pressures, presence of faults and/or fractures, presence of improperly plugged wells within the area of influence of the injection well, will all have to be taken into consideration.

3. The subsurface depth of the injection zone in the proposed exempted aquifer is also important. No minimum depth in deep, confined aquifers can be specified as this will depend on the geologic, hydrologic and engineering characteristics at a particular injection facility. However, injection into surface aquifers is not recommended due to lack of a confining interval and the possibility of hydraulic communication.

4. The subsurface depths of the deepest water wells in the vicinity of the proposed exempted aquifer will also have to be taken into consideration. A vertical separation of at least several hundred feet between the base of the deepest water well and the top of the proposed injection interval will be necessary. Again, hydrogeologic and engineering characteristics at the proposed injection facility will also have to be evaluated, as this will determine the minimum separation required.

5. The chemistry of the native formation fluid prior to any injection is another important criterion in evaluating an aquifer exemption request. If it is already so contaminated, that it would be technologically or economically impossible to render that water fit for human consumption, then it may meet the requirements of aquifer exemption. On the other hand, if the native groundwater is capable of being a potential USDW and the costs to treat the

water to drinking water quality standards are reasonable, then the request for aquifer exemption may be denied.

6. An estimate of the portion of the aquifer around each injection facility that should be exempted to provide storage for injected fluids for the proposed life of the plant without contaminating USDW's above the injection zone must be available. This in turn will depend on the volume of fluid to be injected over the life of the plant and on the effective thickness and effective porosity within the injection zone. An example calculation to determine the radial displacement of injected fluid from a well bore is shown in Chapter IV.

7. In a fractured system, estimates of the effective porosity of the fractures, vugs and solution channels have to be known. Otherwise the distance of migration of the injection fluids may be incorrect by an order of magnitude. Since the fractured pathways have a lower resistance to flow, fluid moves more faster than through the matrix, resulting in a shorter travel time and early breakthrough.

8. Estimates of the vertical and horizontal permeability within and connected to the injection zone is also an important parameter. This is especially important in determining the possibility of vertical communication between the injection zone and an overlying USDW. This data can be obtained from core analysis or from well tests.

9. Estimates of the effective migration distance possible from the injection well will also have to be made. Several analytical and numerical techniques are available to estimate the radius of migration. A simple radial displacement calculation is shown in Chapter IV. It should be noted that these estimates are only approximate and therefore have to be used with caution. It is also recommended that a buffer zone be added to the calculated distance.

10. The availability and quality of alternative water supply sources in the vicinity of the proposed exempted aquifer is also a significant factor. When an adequate supply of good quality water is available from alternative water supply sources, then the proposed aquifer may be considered for exemption if the other exemption criteria are also satisfied. Also, if the quality of the proposed exempted aquifer is poor (greater than 8,000 to 10,000 mg/l TDS and not likely to be used for drinking water purposes) as compared to the quality of alternative water supply sources (TDS less than 8,000 mg/l), then the proposed aquifer may be considered for exemption.

11. An analysis of future water supply needs within the general area of the proposed exempted aquifer will have to be done when evaluating an aquifer exemption water request. The availability of adequate water from alternative water supply sources to supply the future needs of the community will

determine whether the proposed exempted aquifer may be exempted or not.

12. Distance from the proposed exempted aquifer to public water supplies and alternative water sources will also have to be taken into consideration when evaluating an aquifer exemption request. The greater the distance the water has to be transported, the greater will be the pipelining costs and this in turn will increase the costs of supplying water to the community.

13. Costs to develop the proposed exempted aquifer as a water supply source and costs to develop alternative water supplies will also have to be determined. Costs to recover and treat the groundwater to potable standards will have to be developed and these costs will have to include well construction and transportation costs. The availability of treatment and estimated costs to remove contaminants from water will depend on the chemical content of the proposed injected fluids and the extent and approximate location of the contaminant plume within the aquifer. In some instances, it may be technologically or economically impossible to remove the contaminants and restore the aquifer to pre-contamination standards. Such an aquifer may qualify for exemption, again if the other exemption criteria are satisfied. An example calculation for determining the economic costs is shown in Chapter VII.

The guidelines presented in this section are not to be considered individually when evaluating an aquifer exemption request. Instead, each aquifer exemption request will have to be evaluated on a case by case basis and all the guidelines presented will have to be considered collectively. It should be noted that even if several of the exemption criteria are satisfied, EPA has the discretion to decline to exempt an aquifer, if other considerations warrant maintaining the USDW classification.

Quality of Hydrogeologic Data

The considerable depths of the injection wells and the resultant high costs of sampling and logging impede collection of sufficient and representative hydrogeologic and water quality data. In order to help EPA in its decision making process, guidelines on the following general issues are presented.

1. Reliability of water quality data, primarily salinity profiles.

   Fluid samples to determine water quality are usually obtained at the surface or from the subsurface using downhole fluid samplers. Water quality data can also be obtained from borehole geophysical logs. When fluid samples are obtained at the surface, it is important that the well be pumped for at least one well bore volume before the samples are taken. Also the well must have stabilized for at least a few hours prior to sampling. Stabilized flow conditions are also important prior to taking down hole fluid samples. The samples have to be provided and shipped to the laboratory using standard EPA procedures, depending upon the composition of the subsurface fluid.

2. Reliability of data derived from geophysical logs.

Geophysical logs usually provide good data relating to subsurface rock and fluid properties. In most cases only qualitative interpretations can be made, but quantitative evaluations can also be made from some logs.

The reliability of the data obtained from logs is heavily dependent on the knowledge and expertise of the log analyst. Also, the hole conditions under which the logs were run have to be taken into consideration. Some logs are affected by the type of fluid in the hole. The type of casing also affects certain logs. Log readings are usually very shallow, in the immediate vicinity of the well bore and may not yield representative data on the formation characteristics further away from the wellbore, which in fact represent the true formation characteristics. Finally, logging data may be incorrect as suspect due to tool malfunction or due to the tool not being calibrated prior to the logging run.

For a proper analysis of subsurface formation characteristics, not only must data from geophysical log interpretation be evaluated, but also data from core analysis, completion and testing data, injection data and any other reservoir data that may be available. With this approach, the data obtained is fairly reliable.

3. What constitutes a representative deep well water quality sample.

Since the UIC regulations stipulate that any aquifer is a USDW if it contains water with less than 10,000 mg/l TDS, the water quality in the proposed injected zone becomes critical in evaluating an aquifer exemption request. In some instances, the samples obtained from the injection zone may not represent true injection zone properties. For example, if there is vertical communication between the injection zone and any overlying or underlying aquifers, the water in the injection zone will show interference effects from the other aquifers. The results obtained will not represent true water quality in the injection zone. Vertical communication can also result due to improperly plugged wells or poorly cemented wells in the vicinity of the test well. If the injection zone is adequately isolated from overlying and underlying strata, then representative deep well samples can be obtained either by using wireline downhole fluid samples, or by flowing the well to the surface (sample to be taken after unloading at least one well bore volume of fluid).

In some instances, water quality data in deep wells is obtained from drill stem tests (DST). If the tool is opened for at least a 20 to 30 minute flow period and a successful test is performed then the data may be reliable. However each test will have to be evaluated individually, to make sure that the sampling interval was isolated and that there were no interference effects from other zones.

CHAPTER III

UNDERGROUND INJECTION CONTROL CRITERIA FOR AQUIFER EXEMPTION

Background

The Underground Injection Control (UIC) program is designed to protect all underground sources of drinking water (USDW's) except in cases where an exemption is allowed pursuant to 40 CFR Sec. 146.4. A USDW is defined in 40 CFR Sec. 146.3 as an aquifer or its portion:

1. (i) Which supplies any public water system; or
   (ii) Which contains a sufficient quantity of groundwater to supply a public water system; and
      a. currently supplies drinking water for human consumption; or
      b. contains fewer than 10,000 mg/l total dissolved solids; and
2. Which is not an exempted aquifer.

This definition includes all aquifers that have a capability of supplying water for human consumption regardless of whether the aquifers are presently being used for that purpose.

Use of Aquifers for Water Supply

An aquifer is defined in 40 CFR Sec. 146.3 as a geological formation, group of formations, or part of a formation that is capable of yielding a "significant" amount of water to a well or spring. EPA has not set a numerical value for "significant" yield, which will vary from place to place depending on water requirements, water availability, and economic factors. The aquifer yield will also depend on the spacing and the number of wells tapping the aquifer. Hydraulic conductivity (k) can be used to differentiate between "good aquifers" and "poor aquifers". Davis and DeWiest (1966) and Todd (1959) define "good aquifers" as having k values greater than 10 gpd/ft^2 and "poor aquifers" as having k values less than 10 gpd/ft^2.

The quality of groundwater used for drinking water purposes is generally less than 10,000 mg/l total dissolved solids (TDS). Groundwater containing several thousand mg/l of total dissolved solids is rarely used for human consumption or for irrigation. There are, however, a few locations in the Southwestern U.S. where water containing more than 4,000 ppm of dissolved solids is used continuously for irrigation. In some areas of the Southwest and the Great Plains, supplies containing as much as 2,500 ppm are used for drinking by people who have become accustomed to such water (Water Atlas of the United States, 1973). Figures 1, 2, and 3 show the quality of groundwater currently being used for human consumption by the rural population (including population centers smaller than 10,000 persons) in Arizona, California and Nevada.

As a general rule, the total dissolved solids content of groundwater increases with depth and with the length of time that the water has travelled through the aquifer from a point of recharge to a point of discharge. Groundwater quality may be

Arizona

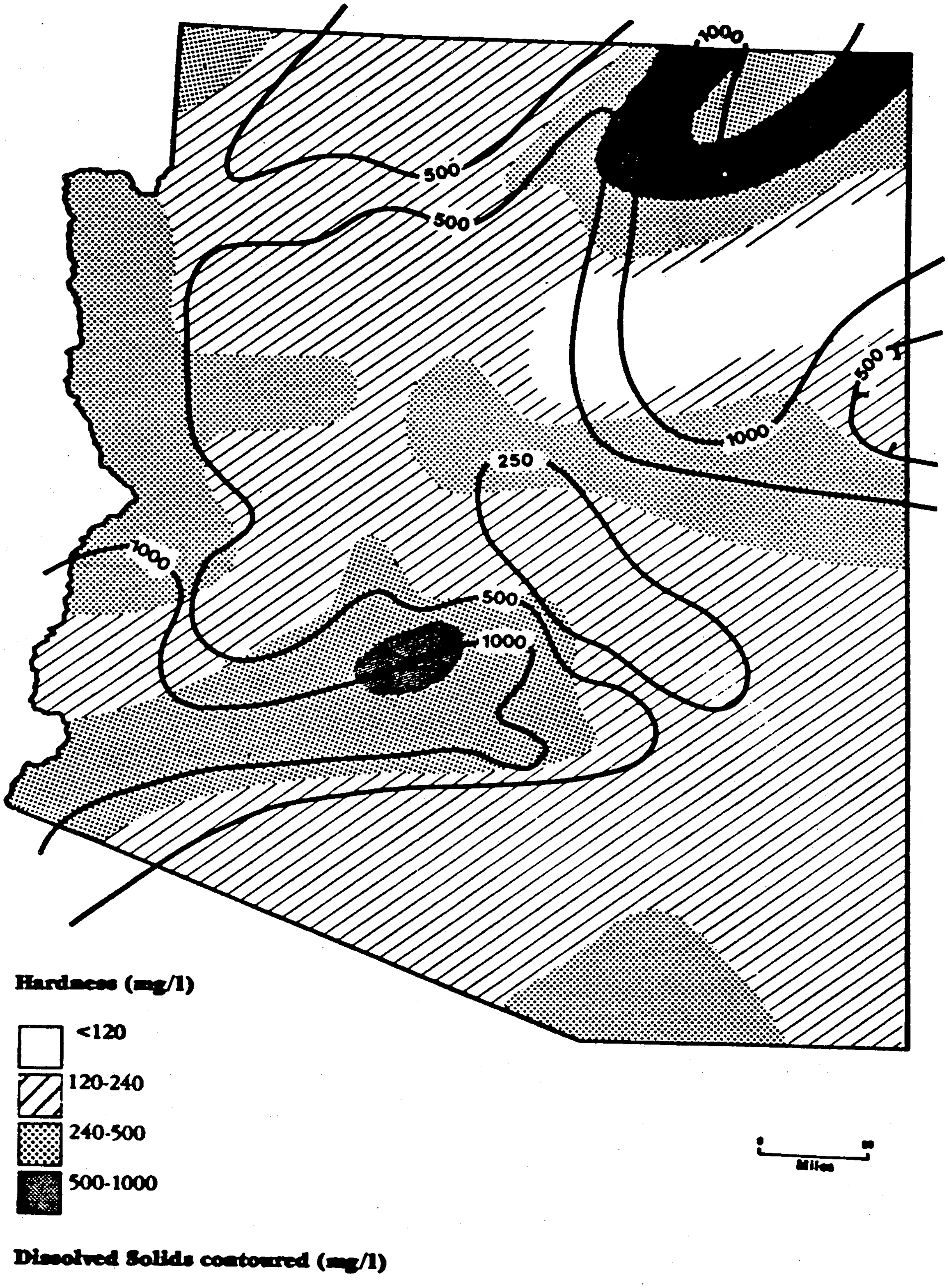

FIGURE 1

Quality of water used for human consumption in Arizona.

California

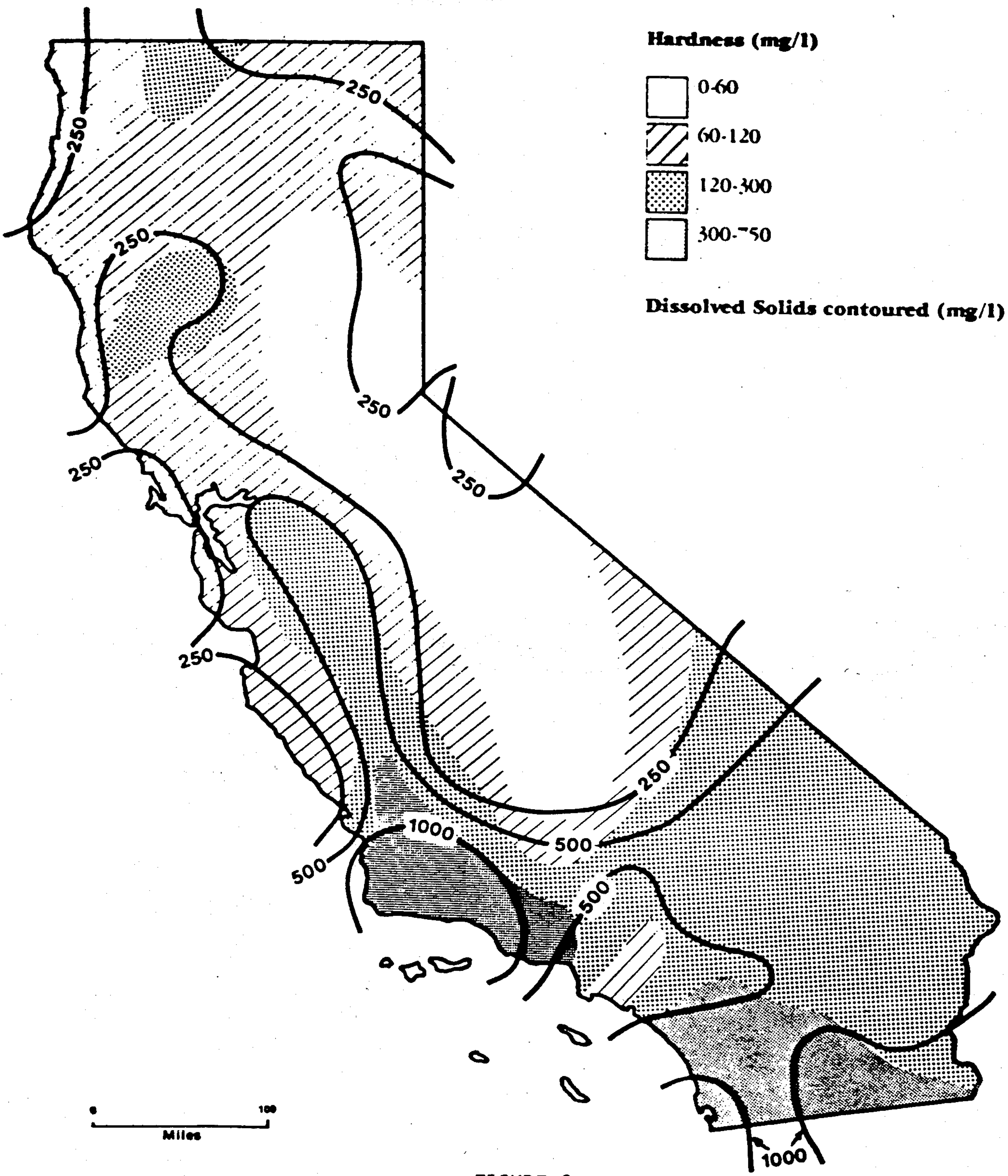

FIGURE 2

Quality of water used for human consumption in California.

Nevada

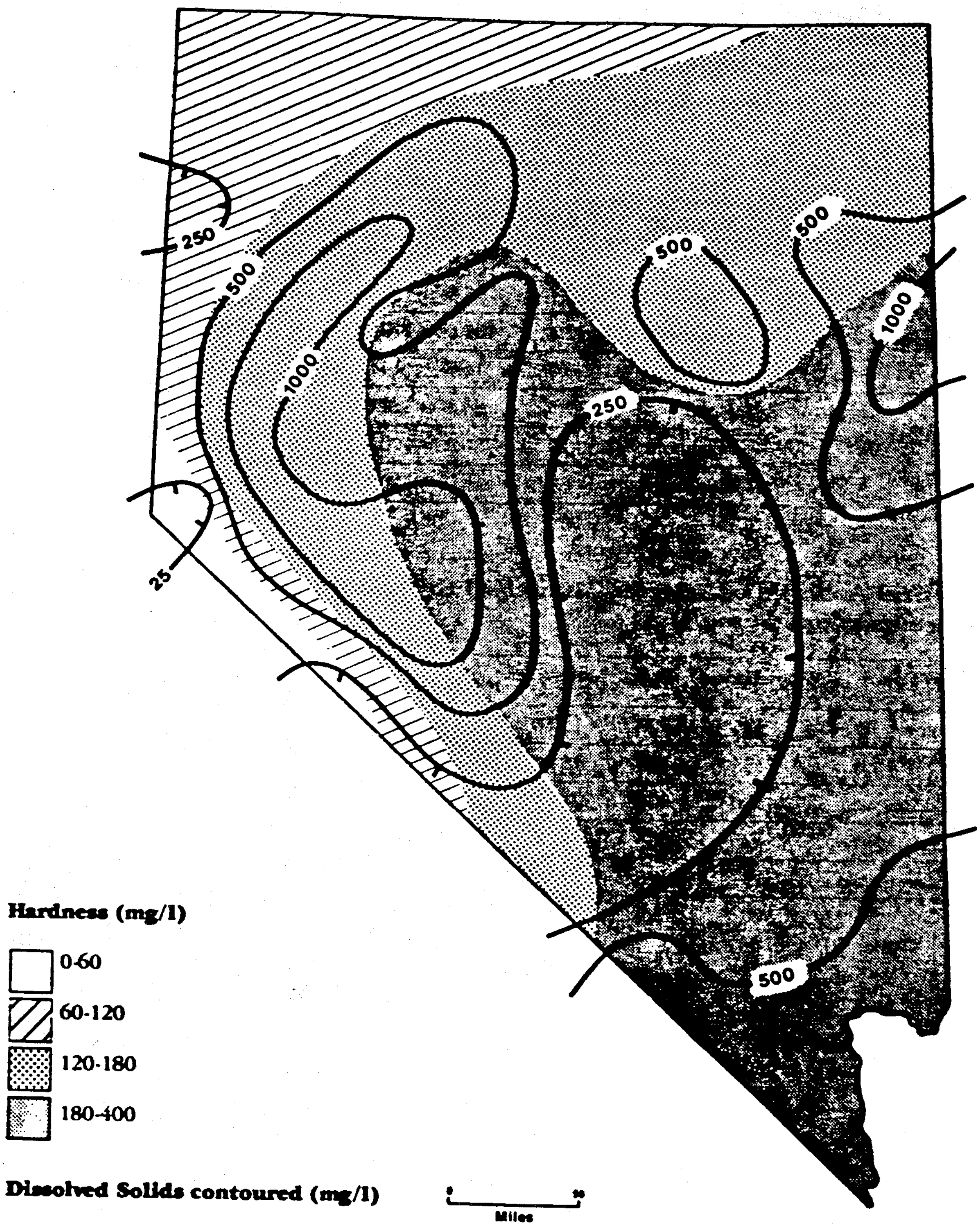

FIGURE 3

Quality of water used for human consumption in Nevada.

locally degraded by waste disposal practices, spills, application of chemicals (de-icing salts, pesticides, and fertilizers), drainage modifications, and other factors.

The withdrawal of groundwater specifically for human consumption constitutes only about 17 percent of all uses of groundwater in the nation. The principal use of groundwater is for irrigation (67 percent), with another 14 percent being pumped for industrial purposes. Tables 1 and 2 list EPA's primary and secondary drinking water standards while Table 3 lists the preferred maximum concentrations of several constituents in water acceptable for irrigation and industrial uses.

Use of Aquifers for Other Purposes

A USDW may be used for several purposes other than to produce water. It may be tapped for oil, gas or geothermal energy or it may be mined for minerals. For underground storage of gas, an important practice in some parts of the nation, it may be necessary to withdraw the existing groundwater before the gas can be introduced into the aquifer for storage.

Use of USDW's for waste storage and disposal is a widespread practice, generally looked upon as undesirable or illegal. The wastes may be introduced into the subsurface deliberately or inadvertently from sources such as septic tanks, leaky pipelines, surface impoundments, landfills, highway runoffs, spills, or applications of fertilizers and pesticides. Generally, the USDW's that are most affected are the shallowest ones.

Table 1

EPA Interim Primary Drinking Water Standards

Constituent	Maximum Level (mg/l)
Arsenic	0.05
Barium	1.0
Cadmium	0.01
Chromium	0.05
Fluoride	1.4 - 2.4
Lead	0.05
Mercury	0.002
Nitrate (as N)	10
Selenium	0.01
Silver	0.05
Endrin	0.0002
Lindane	0.004
Methoxychlor	0.1
Toxaphene	0.005
Chlorophenoxy 2,4-D	0.1
Chlorophenoxy 2,4,5-TP Silvex	0.01
Radium	5 pCi/l (where PCi is picocurie)
Gross Alpha	15 pCi/l
Gross Beta	4 million
Turbidity	1/TU (where TU is turbidity unit)
Coliform Bacteria	1/100 md

Table 2

EPA Secondary Drinking Water Standards

Constituent	Maximum Level (mg/l)
Chloride	250
Color	15 color units
Copper	1
Corrosivity	Non-corrosive
Foaming agents	0.5
Iron	0.3
Manganese	0.05
Odor	3 Threshold Odor Number
pH	6.5 - 8.5
Sulfate	250
Total Dissolved Solids	500
Zinc	5

Table 3

Water Quality Criteria for Industry and Irrigation

Constituent	Irrigation (mg/l)	Industry (mg/l)
Alkalinity	--	40-500
Aluminum	1.0	0.01-5
Ammonia (as N)	--	0.1-0.7
Arsenic	1.0	--
Beryllium	0.5	--
Bicarbonate	--	48-600
Boron	0.75	--
Cadmium	0.005	--
Chloride	--	200-1,000
Chromium	5	--
Cobalt	0.2	--
Copper	0.2	0.01-0.5
Hardness (as $CaCo_3$)	--	100-850
Iron	--	0.01-1
Lead	5.0	--
Manganese	2.0	0.01-5
Magnesium	--	12-36
Molybdenum	0.005	--
Nickel	0.5	--
pH	--	5-10
Selenium	0.05	--
Silica	--	0.01-50
Sulfate	--	200-620
Total Dissolved Solids	5,000	1,000
Vanadium	10	--
Zinc	5	--

Criteria for Exempted Aquifers

The regulations (40 CFR Sec. 146.4) stipulate that a USDW may be exempted from coverage if it meets the following criteria:

a. It does not currently serve as a source of drinking water; and

b. It cannot now and will not in the future serve as a source of drinking water because:

   1. It is mineral, hydrocarbon, or geothermal energy producing, or can be demonstrated by a permit applicant as part of a permit application for a Class II or III operation to contain minerals or hydrocarbons that considering their quantity and location are expected to be commercially producible.

   2. It is situated at a depth or location which makes recovery of water for drinking water purposes economically or technologically impractical.

   3. It is so contaminated that it would be economically or technologically impractical to render that water fit for human consumption; or

   4. It is located over a Class III well mining area subject to subsidence or catastrophic collapse, or

c. The total dissolved solids content of the groundwater is more than 3,000 and less than 10,000 mg/l and it is not reasonably expected to supply a public water supply system.

EPA's aquifer exemption mechanism was promulgated because of the Agency's decision to adopt a very broad definition of USDWs. This broad definition ensures that any aquifer even potentially usable as drinking water will be considered a USDW, but also results in classifying as USDW's some aquifers that are contaminated, inaccessible, or otherwise unsuitable or unlikely to be used as drinking water. The broad definition allows exemptions from classification as USDWs, after evaluation and review by EPA on a case by case basis. EPA however, has the discretion to decline exemption to an aquifer, even if it meets one of the criteria, if other considerations warrant maintaining the USDW classification. Inherent in this discretion to approve or deny is the discretion to limit the exemption to particular type of practices (single class of wells).

CHAPTER IV

GEOLOGIC AND HYDROLOGIC FACTORS IN EVALUATION OF AQUIFER EXEMPTIONS

Knowledge of the geologic and hydrologic characteristics of the subsurface environment is fundamental to the evaluation of the suitability of exempting an aquifer for waste disposal purposes. The lithology, thickness, areal distribution, structural configuration and engineering properties comprise the geologic environment, while the hydrologic environment includes the chemical and physical properties of subsurface fluids and the nature of the local and regional subsurface flow system. Additional factors that have to be considered in an aquifer exemption evaluation include the total volume of fluid to be injected over the life of the plant, the estimated migration distance of the injected wastewater from the injection well over the life of the plant, and the subsurface depths of the deepest water wells in the vicinity of the proposed exempted aquifer. The geologic and hydrologic characteristics are defined and briefly discussed in this chapter with reference to wastewater injection and aquifer exemption. Other factors critical in evaluating an aquifer exemption request are also presented and discussed.

Economic considerations such as availability and quality of alternative water supply sources, aquifer restoration costs, costs to develop alternative water supplies etc. are not presented here. There are discussed in detail in the next chapter which covers economic considerations in evaluating an aquifer exemption request.

Injection and Confining Intervals

Vertical sequences of rocks that occur in the subsurface are conventionally subdivided by geologists into groups, formations, and members, in descending hierarchy. That is, members are subdivisions of formations and formations subdivisions of groups. Use of these terms implies mappable (traceable) rock subdivisions. However, such subdivisions may not be entirely suitable when discussing subsurface flow systems, because the engineering properties of porosity and permeability often do not respect geologic boundaries. To overcome this problem, hydrologists developed the terms aquifer, aquiclude, aquitard, and aquifuge to describe rock subdivisions in terms of their capacity to hold and transmit water. An <u>aquifer</u> is defined as a formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs. Conversely, an <u>aquiclude</u> stores water, but does not transmit significant amounts. An <u>aquitard</u> lies between the two previously defined types in that it transmits enough water to be regionally significant, but not enough to supply a well. An <u>aquifuge</u> neither contains nor transmits water (Davis and DeWiest, 1966). In wastewater injection, other terms are more commonly used. Actual or potential receiving aquifers are commonly called the <u>injection intervals</u>, zones, units or reservoirs and the intervening strata between the top of the injection interval to the base of the overlying USDW are referred to as confining intervals (aquicludes) or semi-confining intervals (aquitards). The basement sequence of igneous or metamorphic rock that lies beneath the sedimentary rock cover is generally non-porous and impermeable (aquifuge).

Good injection intervals must have sufficient porosity, permeability, thickness, and areal extent to permit the rock to act as a liquid-storage reservoir at safe injection pressures.

An adequate confining interval must be sufficiently thick, extensive and impermeable so that the waste is confined within the injection interval and no migration takes place into overlying USDW's. In many cases, this is not a problem, since the injection interval is so deep and the confining interval so thick and impermeable that there is no need for detailed analysis. However, in other instances, the confining interval is relatively thin, shallow, of questionable permeability, is affected by local structural or stratigraphic geologic features, or is penetrated by abandoned wells that may be improperly plugged. Procedures for the evaluation of confining strata for containment of injected wastewater and for calculation of the flow of wastewater through confining layers are presented by Warner et al (1984).

Reservoir Rock Types

Reservoir rocks can be classified based on their origin into three groups: (1) fragmental (clastic); (2) chemical and biochemical (precipitated); (3) miscellaneous. Alternatively, they can be classified as igneous, metamorphic, and sedimentary. Sedimentary rocks generally make good injection intervals as they possess sufficient porosity, permeability, thickness, and areal extent.

Sandstone, limestone, and dolomite are types of sedimentary rock commonly porous and permeable enough in the unfractured state to be suitable injection reservoirs. Naturally fractured limestone, dolomite, shale and other rocks may also be satisfactory under certain conditions.

Unfractured shale, clay, siltstone, anhydrite, gypsum, salt and basalt have been found to provide good seals against upward or downward flow of fluids.

Stratigraphy

Stratigraphy or stratigraphic geology is the study of the composition, sequence, thickness, age and correlation of the rocks in a region. A stratigraphic study of injection and confining intervals is a fundamental step in the evaluation of a proposed exempted aquifer for wastewater injection purposes. Such studies utilize all available relevant surface and subsurface geologic data which are displayed in the form of stratigraphic columns, cross-sections, fence diagrams, isopach maps and facies maps.

A columnar section is a graphic representation of the rock units present at a location or in a region. Cross-sections shows the thickness of rock units along a selected line and isopach maps show the thickness over an area.

Facies refers to changes in the composition of sedimentary rocks as they are traced laterally and this can be important especially if it occurs in the confining interval. The most significant lithofacies changes in reservoir rocks occur where a permeable rock grades into a less permeable rock. Such changes are of great importance in production of oil and gas and in the regional movement of fluids through the reservoir rock. Some types of facies maps are ratio maps, percentage maps, and isolith maps.

Structural Geology

Structural geology is concerned with the folding, faulting, and fracturing of rocks and the geographic distribution of these features.

Structural geologic characteristics of a region are significant because of their role in influencing subsurface fluid flow, and the engineering properties of rocks. Sedimentary rocks may be folded into synclines (downward or trough-like folds) or anticlines (upward folds). For instance, synclinal basins are viewed as particularly favorable for wastewater injection.

Fractures, which include faults and joints, are of particular concern when evaluating the adequacy of confining intervals. Faults are fractures in the rock sequence along which there has been displacement of the two sides relative to one another. Such fractures may range from inches to miles in length, and displacements are of comparable magnitudes.

Faults may act either as barriers to fluid movement or as channels for fluid movement. Since, in most cases, it is initially difficult to determine whether a fault is a barrier or a flow path, it would be appropriate to assume any significant fault to be a flow path. Subsequently, as a consequence of this assumption if the fault is an environmental hazard, then it may be necessary to either abandon the project or to test the fault directly by pumping or injection testing. A significant fault may be defined as one that is of sufficient length, displacement, and vertical persistence to provide a means of travel for injected wastewater to an undesirable location (Warner et al, 1984).

A fracture along which there has been no movement is referred to as a crack or joint, to distinguish it from a fault. Cracks and joints are important sources of porosity and permeability in some aquifers but can be undesirable when they channel fluids rapidly away from an injection well in a single direction or where they provide flow paths through confining strata.

Engineering Properties of Rocks

The engineering properties of reservoir rocks must be known in order to make a quantitative evaluation of the effects of wastewater injection into an aquifer. The engineering properties include porosity, permeability, compressibility, transmissivity storage coefficient, Poisson's ratio, pressure, and temperature. Each of these is discussed briefly below.

Porosity

Porosity is defined as the ratio of the void space in a rock to the bulk volume of that rock, or,

$$\phi = \frac{V_v}{Vt},$$

where ϕ = porosity, expressed as a fraction;

V_v = volume of void space or pore volume;

Vt = bulk or total volume of rock sample.

Total porosity is a measure of all void space within a sample; whereas, effective porosity is based on the volume of interconnected voids. Hydraulic properties of a rock unit are best defined using effective porosity, since only interconnected voids are available for fluid flow through the rock.

Porosity may be further defined as primary or secondary. Primary porosity is developed during original deposition of the material and is typified by the intergranular porosity of sandstones and the intercrystalline and oolitic porosity of some limestones. Secondary porosity results from mechanical alteration of the porous media by fracturing, solution channelling and from recrystallization and dolomitization. Intergranular porosity occurs in sands and sandstones, and values are dependent upon the grain size, sorting, shape, mineralogic composition, and degree of cementation and compaction. Porosity is best determined using borehole geophysical techniques correlated with laboratory core analysis.

Average porosities in sedimentary rocks range from over 35% in recently deposited, unconsolidated sands to less than 5% for lithified sandstones. Crystalline and microcrystalline limestones and dolomites may have little primary porosity; however, they often exhibit adequate secondary porosity for injection purposes. Typical porosity values range from 10 to 30% for disposal reservoirs and uranium solution mining areas.

Pore volume per unit area is calculated by multiplying total thickness of the injection zone by average porosity. This value determines the displacement of injected fluid into a disposal reservoir. For solution mining, pore volume is used to estimate the amount of water which may be handled during restoration operations to return the injection zone to pre-mining conditions.

The amount of porosity in confining strata is not as important as the form of porosity. Shales have a relatively large total intergranular porosity, but their small pore size makes flow through them difficult. Fractures on the other hand, may contribute only a small amount of porosity but the fractures, if open, may provide transmissive flow paths. Therefore, in a fractured system it is important to consider not only the matrix porosity but also the fracture porosity, as the latter's contribution may be significant.

Permeability

Permeability is a fundamental rock property and is a measure of the capacity of the porous medium to transmit fluids.

Permeability is influenced by the grain properties of rocks and is strongly dependent on grain size. The smaller the grains, the larger will be the surface area exposed to the flowing fluid. Since the frictional resistance of the surface area lowers the flow rate, the smaller the grain size the lower the permeability. Shales, which are formed from extremely small grains, have almost no permeability and therefore make excellent confining layers. Permeability in fractures and solution channels can be several times larger than the matrix permeability.

If CGS units are used, permeability is expressed in cm^2 while the unit of permeability in the petroleum industry is the darcy or the millidarcy, which is one thousandth of a darcy. The darcy is defined as follows:

$$k = \frac{q \mu L}{A \Delta P} \tag{IV-1}$$

where k = permeability in darcys

q = flow rate in cm^3/sec

μ = fluid viscosity in cp

L = length in cm

A = cross-sectional area in cm^2

ΔP = pressure drop in atmospheres.

A simpler form of Darcy's law used in shallow groundwater studies is:

$$k = \frac{q}{A} \frac{dL}{dH} \qquad (L/T) \qquad \text{(IV-2)}$$

where k = hydraulic conductivity

dh = fluid head loss

and other symbols are as previously defined.

The Meinzer unit of the coefficient of permeability, k, is the rate of flow of water in gallons per day through a cross-sectional area of 1 square foot under a hydraulic gradient of 1 foot per foot at 60^{o} F. The Meinzer unit is primarily used in hydrology.

For an injection interval, a permeability of 100-1000 md is considered good to very good while a value of less than 10 md is considered low. Unfractured shales have permeabilities in the order of 10^{-3} to 10^{-6} md and are therefore suitable confining strata.

Permeability is usually determined in the laboratory from core samples or it can be estimated from well tests. Whole core analysis is done when fractures are suspected. The effective permeability may be dependent on the chemistry of the permeating fluid. Presence of clay minerals can cause a permeability reduction, and the degree of permeability reduction to water as compared to air is termed the water sensitivity of a reservoir.

Compressibility

The compressibility of an elastic medium is defined as

$$\beta = \frac{-\delta V}{V \delta p} \qquad [F/L^2]^{-1} \qquad \text{(IV-3)}$$

where β = compressibility of medium (pressure $^{-1}$)

V = volume

p = pressure

Geertsma (1957) states that three kinds of compressibility must be distinguished in rocks: (1) rock-matrix compressibility, (2) rock-bulk compressibility, and (3) pore-volume compressibility.

Rock-matrix compressibility is the fractional change in volume of the solid rock material (grains) with a unit change in pressure. Rock-bulk compressibility is the fractional change in volume of the bulk volume of the rock with a unit change in pressure. Pore-volume compressibility is the fractional change in pore volume of the rock with a unit change in pressure. The reservoir engineer is primarily interested in the change in the pore volume of the rock. The pore-volume compressibility (C_f) appears to vary inversely with rock porosity from 10 x 10^{-6} psi^{-1} for 2% porosity, to 4.8 x 10^{-6} psi^{-1} for 10% porosity, and to 3.4 x 10^{-6} psi^{-1} for 24% porosity (Frick, 1962).

The compressibility of formations waters (C_w) can be determined using correlations developed by Dodson and Standing (1944) and Mcketta and Katz (1947), with 3 x 10^{-6} psi^{-1} representing a good average value. The compressibility of water varies both with temperature and pressure, as is shown in Figure 4. Compressibility enters into flow equations where unsteady or transient flow is concerned.

Transmissivity

Theis (1935) introduced the term coefficient of transmissivity. It is expressed as the rate of flow of water in gallons per day through a vertical strip of the aquifer 1 foot wide and extending the full saturated height of the aquifer under a hydraulic gradient of 100 percent (1 foot per foot). The coefficient of transmissivity is derived by multiplying the coefficient of permeability by the thickness of the aquifer.

Confined and Unconfined Aquifers

A confined aquifer is an aquifer that is confined between two aquitards (relatively impermeable beds). In a confined aquifer, the water level in a well usually rises above the top of the aquifer. If it does, the well is called an artesian well. In some cases the water level may rise above the ground surface, in which case the well is known as a flowing artesian well.

An unconfined or water-table aquifer is an aquifer in which the groundwater encountered by a well is in direct vertical contact with the atmosphere. The water surface fluctuates with the atmospheric pressure and in response to changes in the volume of water in storage in the aquifer. In an unconfined aquifer the

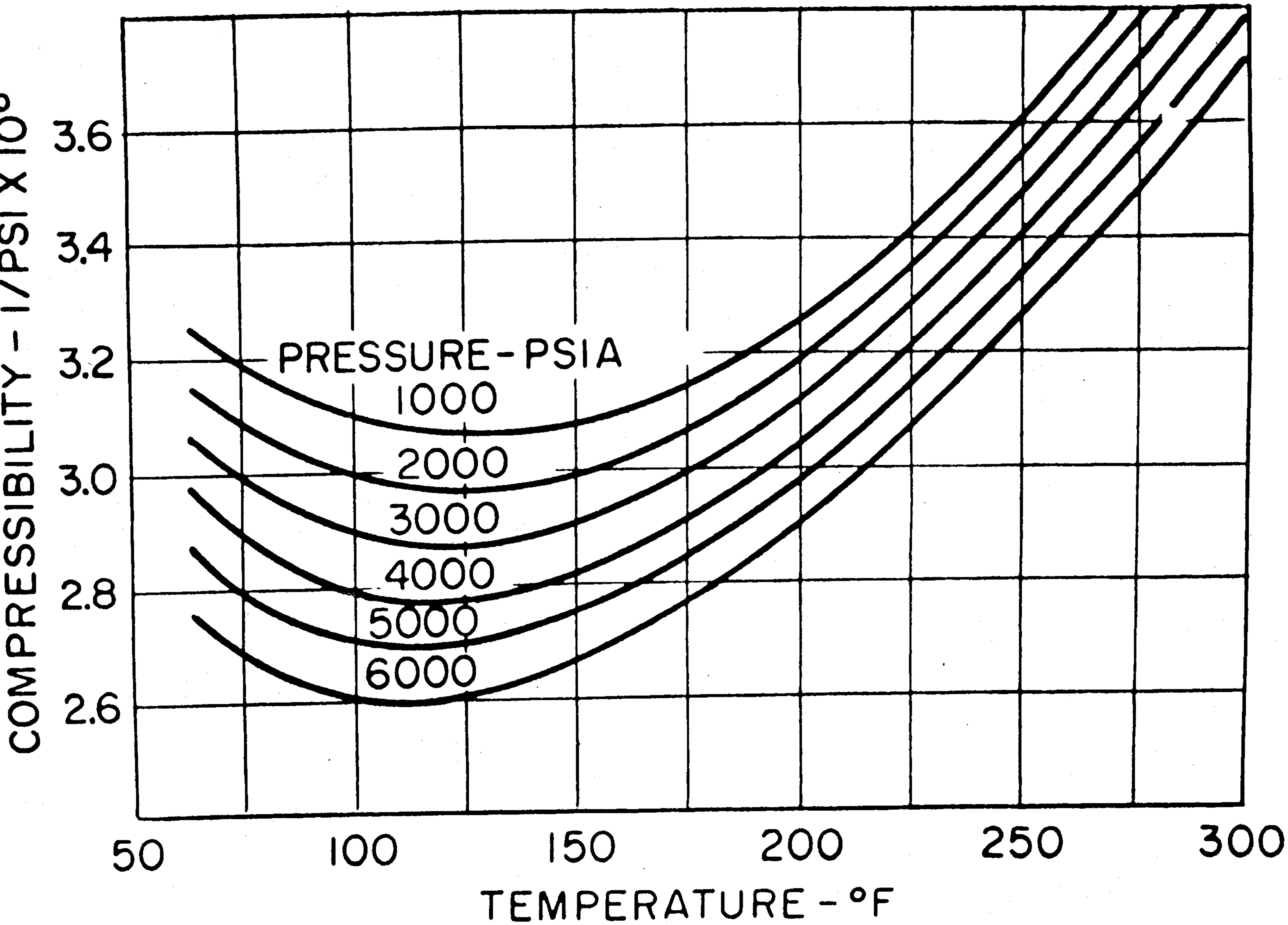

FIGURE 4. COMPRESSIBILITY OF WATER
(KATZ AND COATS, 1968, P. 93).

zone of saturation extends from the underlying confining bed to the water table.

The level to which water rises in well bores defines an imaginary surface called the piezometric surface. For a confined aquifer, the zone of saturation represents complete saturation of the water-bearing formation and is equal to its thickness. The term potentiometric surface applies both to the piezometric surface of a confined aquifer and the water-table surface of an unconfined aquifer. The potentiometric surface is determined by the hydrostatic pressure of water in the aquifer (Lohman, 1972).

The upper and lower boundaries of an injection zone in solution mining are usually defined by confining layers. These beds should be areally extensive, relatively impermeable, and thick enough to prevent the migration of mining solutions from the mining zone to other fresh-water aquifers. Leaching solutions must be confined in the mining zone in order to make contact with the ore and mobilize it for recovery by production wells. By isolating the mining zone, confining beds, not only protect other fresh-water aquifers, but are also economically beneficial to the mining operator by restricting mining solutions to the ore zone, rather than allowing them to migrate to zones which do not contain recoverable ore.

In disposal reservoirs, confining layers serve the same basic functions as in solution mining, confining injected fluids to the injection zone. The total net thickness of shale layers in the intervening strata between the top of the injection zone and the base of the fresh or usable groundwater is an important criterion in determining the adequacy of the confining layer. Other important factors include permeability, areal extent and continuity, presence of faults and/or fractures.

Storage Coefficient

The storage coefficient is the volume of water an aquifer releases or takes into storage per unit surface area per unit change in hydraulic head. Values of S are dimensionless and normally range from 5×10^{-5} to 5×10^{-3} for confined aquifers, and can be determined from aquifer tests or from the equation developed by Lohman (1972):

$$S = \phi \gamma b \left(\beta + \frac{\alpha}{\phi} \right) \qquad \text{(IV-4)}$$

where S = storage coefficient

ϕ = porosity

γ = ρg = specific weight of water per unit area or hydrostatic pressure per foot of aquifer thickness

b = aquifer thickness, inches

β = compressibility of water, square inches per pound

α = compressibility of aquifer skeleton, square inches per pound.

The storage coefficient may also be estimated by multiplying the thickness (h) in feet of the aquifer by 10^{-6}. An example is h = 300 feet, S = 3×10^{-4}, and so on. Values determined by this method are not absolutely correct, as no allowances have been made for porosity or compressibility of the aquifer, but for most purposes they are fairly reliable (Lohman, 1972).

Poisson's Ratio

Competent rocks are generally considered to behave as elastic materials over the range of conditions involved in disposal operations. When stressed either in tension or compression, the rock's dimensions change and these dimensional changes are referred to as strain. The ratio of lateral to axial strain or deformation of an elastic material is Poisson's Ratio. This ratio may be as high as 0.45 for highly elastic rocks and between 0.20 and 0.30 for brittle dense rocks such as limestones and dolomites. Poisson's ratio appears in equations for hydraulic fracturing pressure and is an important determinant in the vertical height of fracture growth.

Reservoir Pressure

Natural bottom-hole pressure in a well is a function of several pressure components: atmospheric pressure, pore pressure, and overburden or lithostatic pressure. Pressure at the water table of an unconfined aquifer and at the potentiometic plane of a confined aquifer is atmospheric. Pore pressure or formation pressure is the pressure experienced by the water in the voids of a porous medium and is measured by the height of water in a piezometer at a particular point. Lithostatic pressure is the pressure caused by the weight of overlying rocks. Pore pressure and overburden pressure are used to predict the fracture gradient of an injection zone.

High pressure injection can cause the initiation or extension of fracturing in the injection zone. Such fracturing is often done intentionally to enhance production of an oil and gas well, but it is highly undesirable to inject waste fluids under sufficient pressure to induce fracturing. Site specific geologic and hydrologic conditions have to be taken into consideration in determining the maximum allowable injection pressure that well prevent fracturing.

In order for underground injection of a fluid to occur, the applied pressure must exceed the natural pressure of the injection zone at the point of injection. This can be accomplished by gravity or by pumping. Injection by gravity occurs when the hydrostatic head of the fluid column exceeds the injection zone pressure. Most wells however, utilize injection pumps for injection purposes.

Injection rates can range from 2 to 3 gallons per minute to over 1500 gallons per minute, with typical wells injecting at several hundred gallons per minute. Subsurface injection of fluid causes a pressure increase in the injection zone near the well bore. A baseline reservoir pressure prior to start of injection is critical in monitoring the pressure buildup due to injection operations and for area of review calculations.

Injection pressures may not be as significant for solution mining operations, due to the much shallower depths of operation and associated reduction of natural pressure. In Texas, a limit of 0.40 pounds per square inch per foot of well depth is specified in each permit as the maximum allowable injection pressure.

Reservoir Temperature

The temperature of the aquifer and its contained fluids is important because of the effect that temperature has on fluid properties. The temperature of shallow groundwater is generally about 2°-3° greater than the mean annual air temperature. Figure 5 shows the approximate temperature of groundwater in the United States. The geothermal temperature gradient increases with depth and averages 1°F-5°F for every 100 feet of depth. Geothermal gradient maps for the United States can be obtained from the American Association of Petroleum Geologists, Tulsa, Oklahoma.

Properties of Subsurface Fluids

Chemistry

The chemistry of the native aquifer water has to be known in order to evaluate whether the aquifer can be exempted for wastewater injection purposes. Chemical analyses of subsurface water are also useful for correlation of stratigraphic units, interpretation of subsurface flow systems and calibration of borehole logs.

In order to evaluate the chemistry of aquifer water, it is necessary to obtain samples after a well is drilled. Geophysical logs are also useful for estimating the dissolved solids content of aquifer water in intervals that are not sampled. The range of

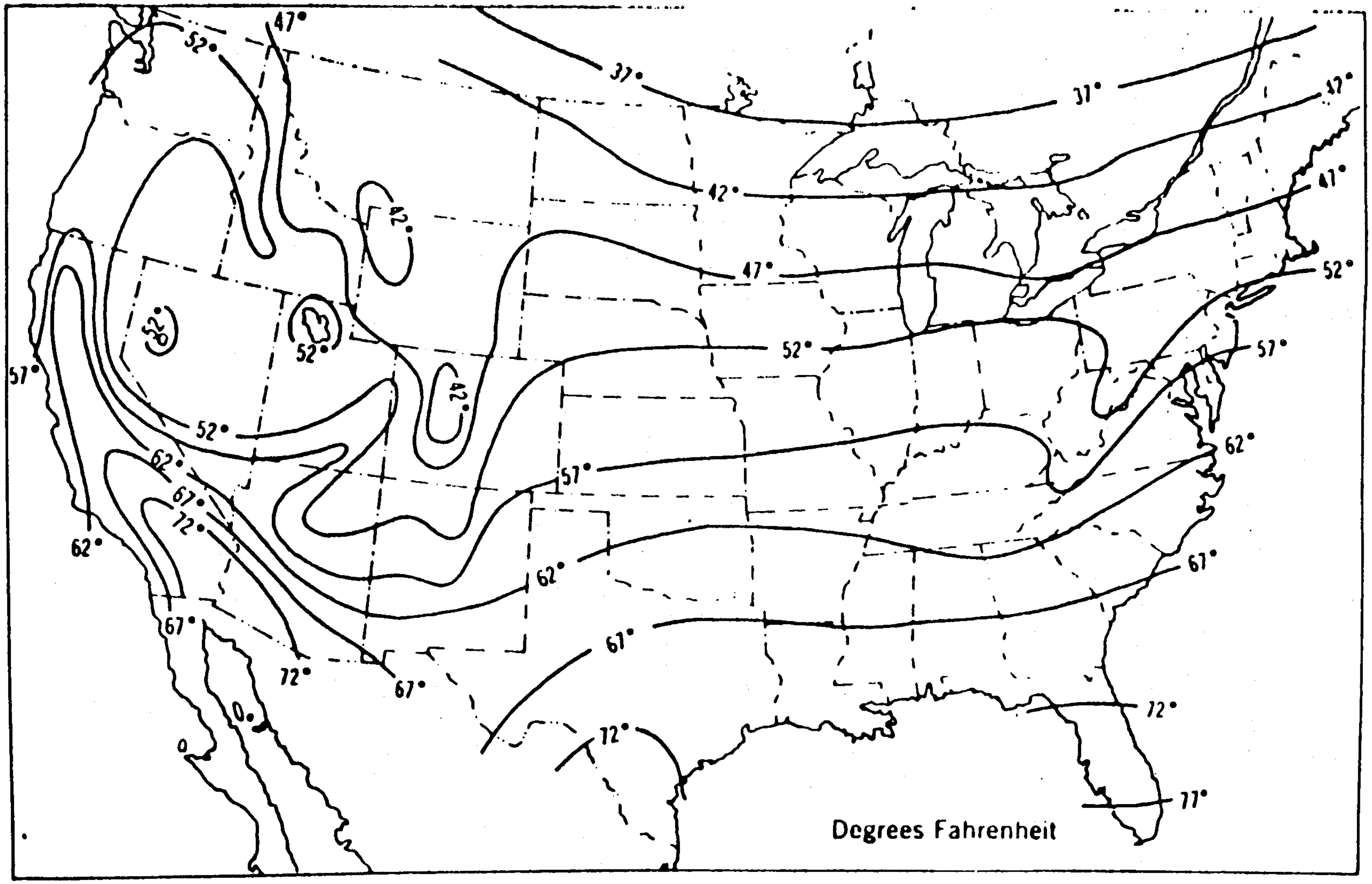

FIGURE 5 APPROXIMATE TEMPERATURE OF GROUND WATER IN THE UNITED STATES AT DEPTHS OF 30 TO 60 FEET (COLLINS, 1925).

dissolved ions that may be present in a subsurface water is so great that a complete chemical analysis is seldom performed. Samples of water taken from shallow fresh water aquifers should be analyzed more completely for minor elements so that their baseline quality is well established and the presence of any later-introduced contaminants can be detected. Aquifer water quality can be illustrated by contour maps which show the concentration of dissolved solids or other selected parameters.

Compatibility

Compatibility of injected wastes with the formation matrix and contained fluids is a potential problem with waste disposal wells. Injected fluid may react with the formation or its natural fluids to form precipitates which can clog the formation in the vicinity of the well bore.

Wastes which may cause undesirable reactions within the injection zone can be treated prior to injection to improve compatibility characteristics. Treatment will vary with waste composition, but usually involves precipitation prior to injection to remove materials which might otherwise precipitate in the injection zone. Removal of suspended solids larger than 1 to 5 microns in size prior to injection is also generally practised.

In cases where a waste stream is incompatible with the formation fluids, a buffer zone composed of a fluid that is compatible with waste fluids and with the formation and its contained fluids, may be injected ahead of the waste.

Theoretically this can prevent direct contact between injected waste and injection zone fluids in order that precipitation either does not occur or it occurs some distance away from the well bore.

In solution mining operations compatibility is seldom a problem. Unless the mining solutions are essentially compatible with formation fluids, leaching of the desired mineral is not possible.

Viscosity

Viscosity is the internal friction or the ability of a fluid to resist flow, and is an important property in determining the rate of flow of a fluid through a porous medium. The absolute viscosity unit in the metric system is the

$$\text{poise} = 1 \text{ dyne. sec/cm}^2 = 1 \text{ gpm/sec.cm}$$

The centipoise (1 cp = 0.01 poise) is used in practically all reservoir engineering calculations.

Kinematic viscosity of a fluid is the absolute viscosity divided by the density. In the metric system the unit of kinematic viscosity is the stoke, expressed as:

$$= \mu/\rho = \frac{\text{poises}}{\text{gm/cc}} = \frac{\text{cm}^2}{\text{sec}}$$

The most commonly used unit of kinematic viscosity is the centistoke (1 cst = 0.01 stoke). Figure 6 shows the variation in viscosity of water with temperature and salinity.

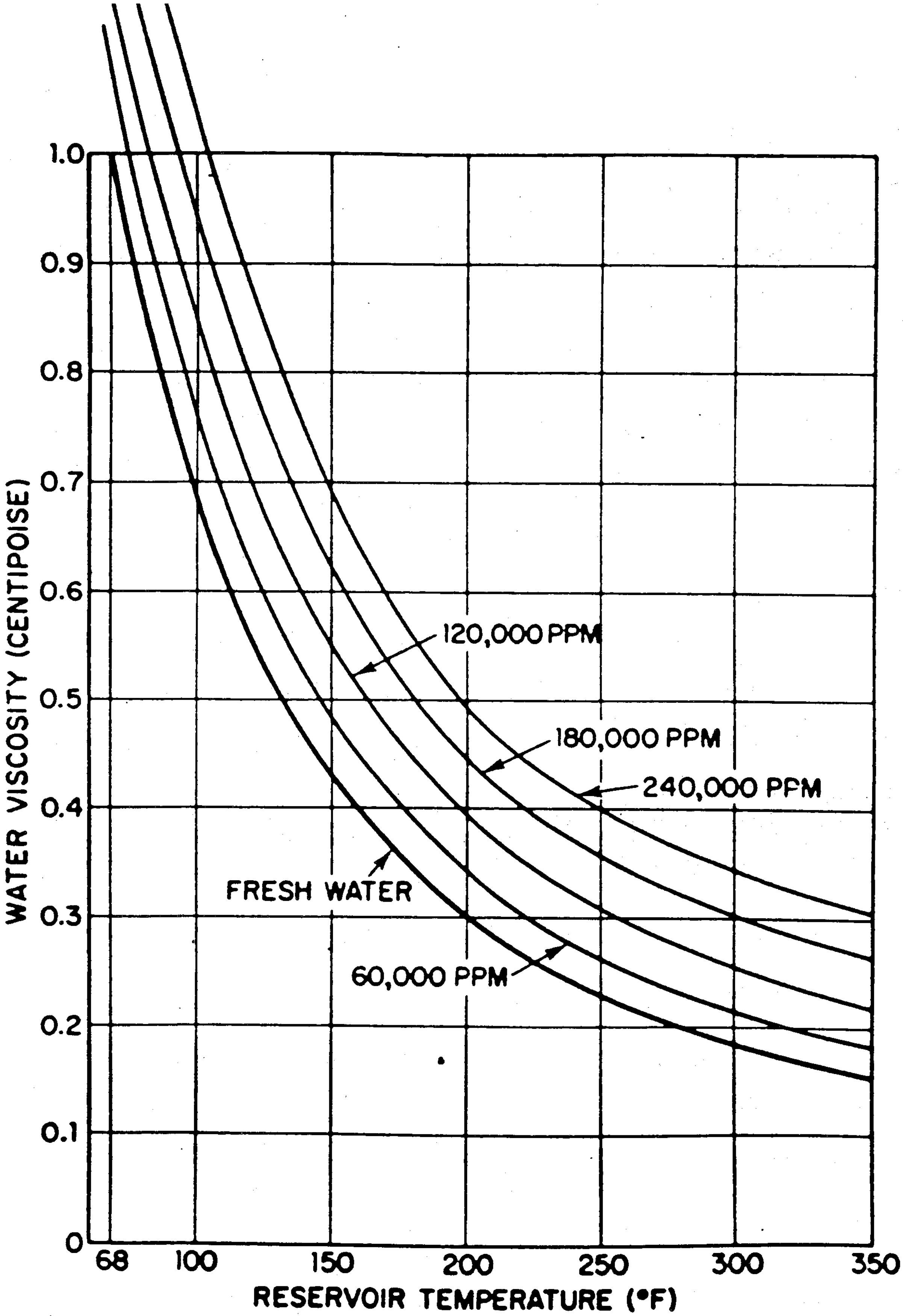

FIGURE 6 WATER VISCOSITY AS A FUNCTION OF TEMPERATURE AND SALINITY (ppm NaCl) (PIRSON, 1963, P. 40).

Density

The density of a fluid is its mass per unit volume. Water density increases with increasing total dissolved solids constant as shown in Figure 7.

Flow Through Confining Layers

The entire purpose of the evaluation of a confining layer or layers for containment of injected wastewater is to provide assurance against vertical migration of wastewater or saline water from the injection unit into overlying fresh water bearing aquifers. Such vertical movement could occur (Warner et al, 1984) as a result of:

1. Intergranular flow through unbreached confining strata.
2. Flow through naturally fractured or faulted confining strata.
3. Flow through confining strata with solution porosity and permeability.
4. Flow through artificially fractured confining strata.
5. Flow through abandoned unplugged or improperly plugged wells.

Some of these conditions are important and are discussed briefly below.

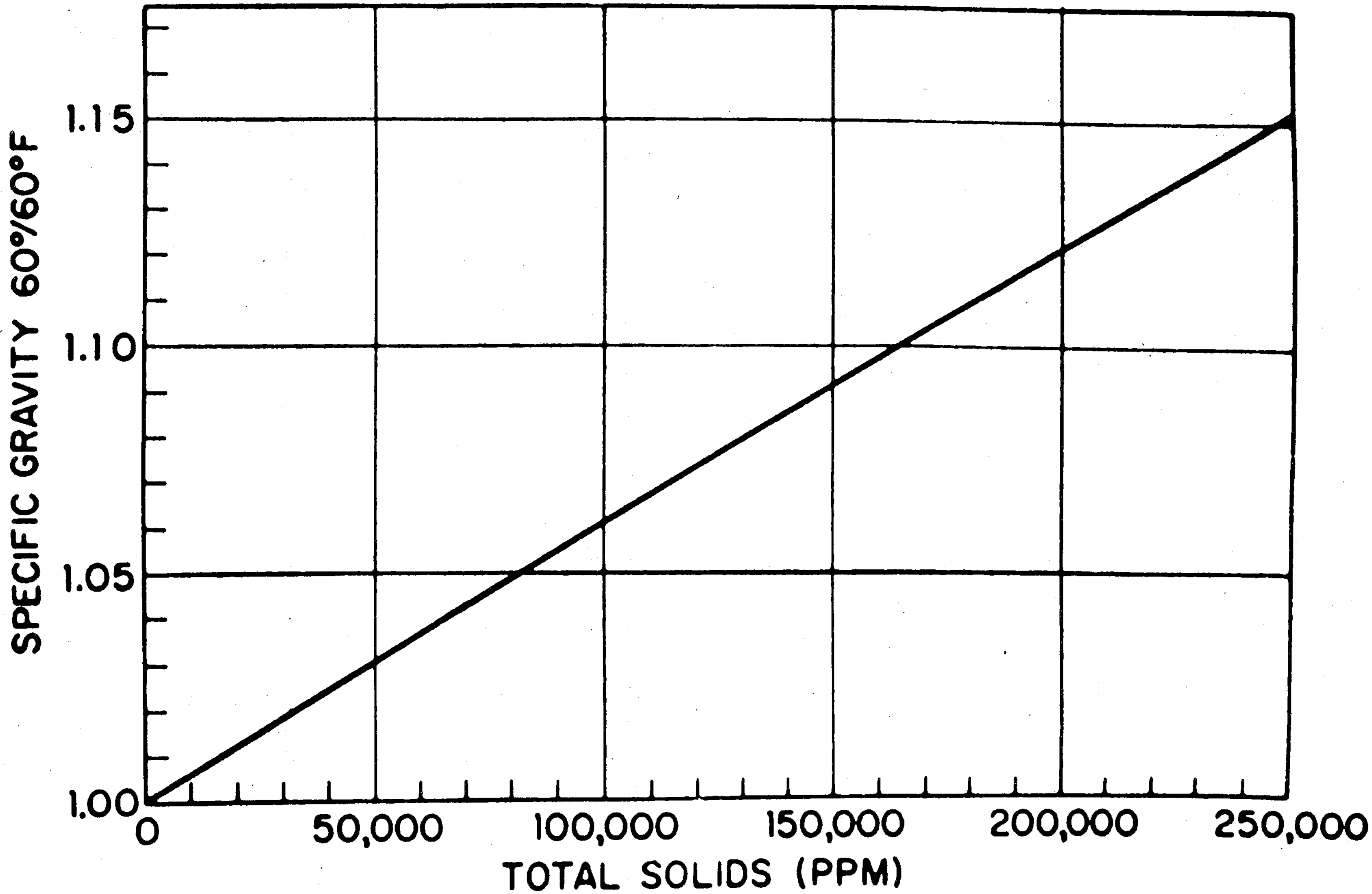

FIGURE 7 SPECIFIC GRAVITY OF WATERS VERSUS TOTAL SOLIDS IN ppm (DATA FOR NaCl SOLUTIONS) PIRSON, 1963, P. 39).

Natural Intergranular Flow

If the confining layer is a clastic sedimentary rock, that is, it is composed of discrete sedimentary particles and is unfractured, then fluid flow will be through intergranular spaces. Shales and siltstones and gradations between them are examples of such rocks. Flow through the intercrystalline spaces in chemically deposited rocks such as limestone is also intergranular flow.

The rate of travel of wastewater vertically in a reservoir can be estimated applying Darcy's law to fluid flow through a granular rock with Darcy's law being expressed as:

$$V = \frac{\bar{K} \, \Delta P}{\mu \, \Delta L} \qquad \text{(IV-5)}$$

where, V = darcy velocity (cm/sec)

$\bar{K}$ = permeability (darcys)

μ = viscosity (centipoises)

ΔP = differential pressure across the flow distance (atmospheric)

ΔL = flow distance (centimeters)

Also, the actual average intergranular liquid velocity is:

$$\bar{V} = V/\phi_e \qquad \text{(IV-6)}$$

where $\bar{V}$ = intergranular velocity (cm/sec.)

ϕ_e = effective porosity

The fluid pressure in a reservoir into which liquid is being injected is greatest at the injection well face and decreases approximately logarithmically away from the well bore. The pressure will also vary with time, increasing as injection continues or declining if injection ceases or the rate is reduced. For purposes of illustration, however, a maximum constant pressure can be assumed to exist at the injection well in order to calculate the rate of vertical wastewater movement through a confining layer. Table 4 shows illustrative rates of movement in feet/year, for a range of pressures and permeabilities. The travel rates shown in Table 4 are only meant to be illustrative. Additional computations can be made using actual field data, if desired.

Numerical models are also available to evaluate flow from an injection zone to an overlying aquifer through a confining or semi-confining interval. One such model is the USGS Saline Water Injection Program or SWIP (Intercomp Resource Development Inc. 1976). Warner et al (1984) have used this model to obtain predicted pressures, vertical velocities and saline water displacements in the injection zones and semi-confining units at St. Petersburg, Florida. Results obtained compared favorably with those obtained by Hickey (1984).

Naturally Fractured Strata

Naturally occurring fractures in a confining layer greatly increase the permeability and create a secondary porosity which though small in magnitude is effectively interconnected. The net

Table 4 **Distance of vertical travel of injected wastewater in feet/year through a 100-foot-thick confining stratum with various permeabilities and pressure gradients. The effective porosity was assumed to be 10 percent and the viscosity to be one centipoise.**

	ΔP (psi)			
K (darcys)	500	1,000	2,000	5,000
1×10^{-3}	114 ft/yr	228 ft/yr	456 ft/yr	570 ft/yr
1×10^{-5}	1.14	2.28	4.56	5.7
1×10^{-7}	1.14×10^{-2}	2.28×10^{-2}	4.56×10^{-2}	5×10^{-2}
1×10^{-9}	1.14×10^{-4}	2.28×10^{-4}	4.56×10^{-4}	5.7×10^{-4}

result is that wastewater transport through a fractured caprock may be tens or hundreds of times more rapid than through the same rock in an unfractured state.

In many cases, flow through fractured caprock and flow through granular media can be analyzed using the same approach; however, if fractures are widely spaced, are of wide aperture, or have directional permeability (anisotropic) other models may be needed (Freeze and Cherry, 1979).

Abandoned Unplugged or Poorly Plugged Wells

An improperly plugged well, penetrating the injection unit, within the radius of pressure influence of the injection well can act as a point leak from the injection unit to overlying aquifers. Warner et al (1984) have presented a simplified approach to estimate such leakage rates.

The pressure in the injection unit at the location of an unplugged bore hole can be calculated using the following equation:

$$\Delta P = 162.6 \frac{q}{Kh} \log \frac{K t}{70.4 \phi \mu c r^2} \qquad \text{(IV-7)}$$

where,

ΔP = pressure buildup, psi

q = flow rate, B/D

K = permeability, md

h = thickness, feet

t = time, days

ϕ = porosity, decimal fraction

μ = viscosity, cp

c = compressibility, psi^{-1}

r = radial distance, feet.

Rearranging,

$$q = \frac{(\Delta P)\ K\ h}{162.6\ \mu \log \left[\frac{K\ t}{70.4\ \phi \mu\ c r^2}\right]} \qquad \text{(IV-8)}$$

Assuming that,

1. ΔP will remain constant,
2. The unplugged well bore provides no resistance to flow,
3. The unplugged well fully penetrates the injection unit and the overlying aquifer,

a value of q can be calculated.

The flow rate q, for both the injection unit and the confining unit must be calculated using the appropriate values for each unit. Then the smaller value of q will be the estimated leakage rate. It should be noted that the values obtained are only rough estimates and should be used with caution. However, they will give an indication of the possible impact of leakage through an improperly plugged well.

The general geological characteristics of an acceptable confining interval are:

1. Sufficient thickness, lateral extent and impermeability to confine waste to the injection interval.

2. The absence of faults or extensive joints that would permit escape of injected wastewater from the injection interval into adjacent aquifers.

Additionally, confining intervals must not be breached by improperly plugged wells or by induced hydraulic fractures that would permit the vertical escape of wastewater into adjacent aquifers.

An extensive array of techniques and tools are available for the geologic and engineering evaluation of confining strata. The extent to which the available methodology is applied will involve economics as well as science and engineering.

Rate and Direction of Wastewater Movement

The rate and direction of movement of the injected fluid within a reservoir depends not only on the hydrogeology but also on the properties of the formation water and the injected wastewater.

A good estimate of the minimum distance of wastewater flow from an injection well can be made by assuming that the wastewater will uniformly occupy an expanding cylinder with the well at the center. Where porosity, permeability, and thickness are uniform in a homogeneous, isotropic medium, distribution of injected wastewater will be in a radial direction. The dip of the receiving bed, which influences the hydraulic gradient of the reservoir, can be disregarded when calculating effluent displacement, if the dip of the beds is of a low order. Then radial distance of migration

$$r = \sqrt{\frac{\text{Cum. Vol. injected (gals.)}}{\pi \times 7.48 \text{ gal/ft}^3 \times h \times \phi}} \tag{IV-9}$$

where r = radial distance of fluid front from well, feet

h = <u>effective</u> reservoir thickness, feet

ϕ = average <u>effective</u> porosity

For example, assume an injection operation as follows:

Injection rate q = 100 gpm

Injection time t = 30 years

Effective porosity = 20%

Effective thickness h = 200 feet

$$r = \sqrt{\frac{100 \times 60 \times 24 \times 30 \times 365}{\pi \times 7.48 \times 200 \times 0.2}}$$

$$= 1295 \text{ feet}$$

In most situations, the minimum radial distance of travel will be exceeded, because of dispersion, density segregation, and channeling through high permeability zones. Flow may also be along preferred pathways due to hydrologic discontinuities (eg. faults), directional permeability (anisotropy), or natural flow gradients.

An estimate of the influence of dispersion can be made with the following equation (Warner & Lehr, 1977):

$$r' = r + 2.3\sqrt{Dr} \tag{IV-10}$$

where r' = radial distance of travel with dispersion

D = dispersion coefficient; 3 feet for sandstone aquifers and 65 feet for limestone or dolomite aquifers.

Equation (IV-10) is obtained by solving the equation presented by Bear (1972) for the radial distance at which the injection front has a chemical concentration of 0.2 percent of the injected fluid. The detailed development of dispersion theory is presented by Bear (1972). The dispersion coefficients given are high values for sandstone and limestone aquifers obtained from the literature.

Then for the above example, assuming a sandstone aquifer,

$$r = 1295 + 2.3 \sqrt{3 \times 1295}$$
$$= 1438 \text{ feet}$$

Though radial displacement is not uniform in all directions, the radial dispersion equation provides a good estimate of the distance of the wastewater front from the well bore. For more complex flow systems other models will have to be used such as Bear and Jacobs (1964) model when the densities and viscosities of the injected and interstitial fluids are the same and Gelhar et als' (1972) model when they are different.

The above models consider the wastewater fluid to be inert. If however, the wastewater is not inert and reacts with the aquifer water or minerals, is affected by bacterial action or decays radioactively, then changes in chemical composition with time and distance will also have to be considered. Models that include chemical effects are Bredehoeft and Pinder (1972), Robertson and Barraclough (1973), Intercomp (1976) and Watson (1984).

In general wastewater flow in unfractured sand or sandstone aquifers will more closely agree with theory than flow in fractured reservoirs or in carbonate reservoirs with solution permeability. Particularly great deviations from predictions may occur in limestone or dolomite aquifers. Therefore to model fractured systems a considerable amount of actual reservoir data will be needed to more closely simulate actual reservoir conditions. Also, the fracture porosity and fracture permeability may be more important than the matrix properties.

CHAPTER V

CLASSIFICATION OF INJECTION WELLS

Under the UIC regulations injection wells are classified into five classes as described below.

Class I Injection Wells

1. Wells used by generators of hazardous waste or owners or operators of hazardous waste management facilities to inject hazardous waste beneath the lowermost formation containing, within one quarter (1/4) mile of the well bore, an underground source of drinking water.

2. Other industrial and municipal disposal wells which inject fluids beneath the lowermost formation containing, within one quarter (1/4) mile of the well bore, an underground source of drinking water.

Class II Injection Wells

Wells which inject fluids:

1. Which are brought to the surface in connection with conventional oil or natural gas production and may be commingled with waste waters from gas plants which are an integral part of production operations, unless those waters are classified as a hazardous waste at the time of injection.

2. For enhanced recovery of oil or natural gas; and

3. For storage of hydrocarbons which are liquid at standard temperature and pressure.

Class III Injection Wells

Wells which inject for extraction of minerals including:

1. Mining of sulfur by the Frasch process

2. Insitu production of uranium or other metals. This category includes only in-situ production from ore bodies which have not been conventionally mined. Solution mining of conventional mines such as stopes leaching is included in Class V.

3. Solution mining of salts or potash.

Class IV - Injection Wells

1. Wells used by generators of hazardous waste or of radioactive waste, by owners or operators of hazardous waste management facilities, or by owners or operators of radioactive waste disposal sites to dispose of hazardous waste or radioactive waste <u>into a formation</u> which within one quarter (1/4) mile of the well contains an underground source of drinking water.

2. Wells used by generators of hazardous waste or of radioactive waste, by owners or operators of hazardous waste management facilities, or by owners or operators of radioactive waste disposal sites to dispose of hazardous waste or radioactive waste <u>above a formation</u> which within

one quarter (1/4) mile of the well contains an underground source of drinking water.

3. Wells used by generators of hazardous waste or owners or operators of hazardous waste management facilities to dispose of hazardous waste, which cannot be classified under 40 CFR Sec. 146.5 (a)(1) or Sec. 146.5 (d) (1) and (2).

Class V Injection Wells

Injection wells not included in Classes I, II, III, or IV. Class V wells include:

1. Air conditioning return flow wells used to return to the supply aquifer the water used for heating or cooling in a heat pump;

2. Cesspools including multiple dwelling, community or regional cesspools, or other devices that receive wastes which have an open bottom and sometimes have perforated sides. The UIC requirements do not apply to single family residential cesspools nor to non-residential cesspools which receive solely sanitary wastes and have the capacity to serve fewer than 20 persons a day.

3. Cooling water return flow wells used to inject water previously used for cooling;

4. Drainage wells used to drain surface fluid, primarily storm runoff, into a subsurface formation.

5. Dry wells used for the injection of wastes into a subsurface formation;

6. Recharge wells used to replenish the water in an aquifer;

7. Salt water intrusion barrier wells used to inject water into a fresh water aquifer to prevent the intrusion of salt water into the fresh water;

8. Sand backfill and other backfill wells used to inject a mixture of water and sand, mill tailings or other solids into mined out portions of subsurface mines whether what is injected is a radioactive waste or not.

9. Septic system wells used to inject the waste or effluent from a multiple dwelling, business establishment, community or regional business establishment septic tank. The UIC requirements do not apply to single family residential septic system wells, nor to non-residential septic system wells which are used solely for the disposal of sanitary waste and have the capacity to serve fewer than 20 persons a day.

10. Subsidence control wells (not used for the purpose of oil or natural gas production) used to inject fluids into a non-oil or gas producing zone to reduce or eliminate subsidence associated with the overdraft of fresh water;

11. Radioactive waste disposal wells other than Class IV;

12. Injection wells associated with the recovery of geothermal energy for heating, aquaculture and production of electric power.

13. Wells used for solution mining of conventional mines such as stopes leaching;

14. Wells used to inject spent brine into the same formation from which it was withdrawn after extraction of halogens or their salts;

15. Injection wells used in experimental technologies.

16. Injection wells used for in-situ recovery of lignite, coal, tar sands, and oil shale.

CHAPTER VI

TECHNICAL CRITERIA FOR AQUIFER EXEMPTION

The provisions for aquifer exemption in the regulations (40 CFR Sec. 146.4) are intended to apply to cases where an aquifer, or a part thereof, is so inaccessible or so disrupted by mining, energy production, or contamination that it would make little sense to think of developing the aquifer as a source of water for drinking water purposes.

The basic reasoning behind aquifer exemption is that factors other than those pertaining to water supply should be given consideration wherever the earth materials are being utilized in some manner for man's economic betterment. An example is where part of a shallow aquifer is being physically removed as the result of quarrying or strip-mining operations. The basic question here comes down to whether the removal of the mineral resource has a greater economic benefit to society than the potential value of the aquifer as a source of water for drinking purposes. It can be argued that the disrupted part of the aquifer does not now serve as a source of drinking water and obviously could never serve as a source once it has been entirely stripped away. The affected portion of the aquifer could be granted exemption status under the UIC regulations. Similar lines of reasoning could be applied where the aquifer is contaminated, where the aquifer is affected by collapse or subsidence due to solution mining of minerals, or where the quality or quantity of water in the aquifer is affected by test holes, geophysical shot holes, oil and gas wells, mine shafts, or surficial and underground mine workings.

A separate criterion for exemption relates to situations where an aquifer is so deep in the earth or so far away from points of water demand that its future exploitation as a source of drinking water would be impractical or too costly. A tradeoff analysis would have to be made to demonstrate that the loss of such an aquifer would be economically and socially acceptable.

Technical Criteria for Aquifer Exemption

The UIC regulations (40 CFR Sec. 146.4) stipulate that a USDW <u>may</u> be exempted from coverage if it meets the following criteria:

1. <u>The aquifer does not currently serve as a source of drinking water.</u>

   This is a fundamental requirement that must be satisfied. Obviously, if the aquifer is currently a USDW, then it cannot be granted exemption status for injection purposes.

2. <u>The aquifer cannot now and will not in the future serve as a source of drinking water because: It is mineral, hydrocarbon, or geothermal energy producing.</u>

   The concept underlying this criterion is that any resource-recovery type of activity may so disrupt an aquifer that for all practical purposes it no longer can be used as a source of potable groundwater. The disruption might result in a drastic reduction in the aquifer yield and quality of the groundwater.

Mining of minerals is accomplished in several different ways, each of which can have its own effects on aquifers. Underground mines, for example, may interfere only with deep aquifers, whereas strip-mining operations may disrupt only the very shallowest of aquifers.

Development of hydrocarbon or geothermal-energy resources typically is from deep zones where the groundwater is likely to be saline. In some oil fields, many hundreds of producing wells and brine-return wells may be in operation simultaneously on relatively small tracts of land. In such cases a trade-off analysis will have to be made between the economic benefits to society resulting from mineral recovery operations and the potential value of the aquifer as a source of water for drinking purposes.

3. The aquifer cannot now and will not in the future serve as a source of drinking water because: It is situated at a depth or location which makes recovery of water for drinking water purposes economically or technologically impractical.

The concept underlying this criterion is that an aquifer may be so deeply buried in the earth or may be at so remote a geographic location from places where the water might be needed that it would be technologically impossible or too expensive to develop it as a source of potable water.

Broadly speaking, potable groundwater in most parts of the country is found only in the uppermost layers of the earth, down to depths of perhaps hundreds of feet. In some regions, the potable water zone is underlain by relatively impermeable rocks, and in others, by brackish or saline waters. Almost everywhere, water wells already exist that partly or fully penetrate these fresh groundwater systems. Also, there are no technological limitations on being able to drill to the bottom of fresh water zones anywhere in the nation.

Large regions of the country are underlain by fresh water aquifers that are only hundreds of feet thick, below which the water is too brackish or saline to serve as USDW's. In most places, the depth to brackish or saline groundwater is not greater than 1000 to 3000 feet. Deeper aquifers east of the Rocky Mountains, such as the Madison Limestone, are now being tested to determine their capacity for development.

The cost of developing potable groundwater from aquifers at any depth is normally not a major consideration in water supply. In the first place, groundwater is usually the cheapest of all sources of water because it can be developed precisely at the points where it is needed. Secondly, groundwater offers an important economic advantage in that the investment for its development can be made in stages as the demand for water increases. This is not normally the case with surface-water systems which have to be completely constructed and paid for even if the full utilization of the system will not be achieved for several years.

An argument for possible exemption might be made in the case of small aquifer systems in remote valleys in mountain ranges such as the Rockies, where no use yet has been made of the groundwater and where it is highly unlikely that anyone else would ever take up residence. However, there are no technologic constraints on being able to develop and transport the water by pipeline to centers of water demand, and the only considerations relate to how much the consumer is willing to pay.

4. <u>The aquifer cannot now and will not in the future serve as a source of drinking water because: The aquifer is so contaminated that it would be economically or technologically impractical to render the water fit for human consumption.</u>

The concept underlying this criterion is that on-going or past activities of man have so contaminated a USDW that there is little likelihood that fresh water could be developed from the aquifer at an acceptable cost. The contamination might be localized, as in the case of a single industrial plant that has allowed large materials of objectionable materials to enter the ground, or it could be regional, as in places where industrial operations have caused widespread contamination over many years.

Treatment of contaminated water to render it fit for drinking purposes can be a complex procedure, with the practicability and cost of the treatment differing widely, depending on the nature of the contaminants and the quantity of water being withdrawn.

5. <u>The aquifer cannot now and will not in the future serve as a source of drinking water because: It is located over a Class III well mining area subject to subsidence or catastrophic collapse.</u>

The concept underlying this criterion is that solution - mining activities may so disrupt an aquifer that it would be impractical to consider using the aquifer for drinking water purposes. Construction of wells for solution mining of minerals involves similar technology but different designs than those utilized in disposal wells. In general, solution mining wells are shallower and contain fewer casing strings than waste disposal wells. Solution-mining processes basically involve the injection of chemicals, hot water or steam to dissolve ores or minerals in the subsurface. The materials dissolved from the earth are then pumped back out through the same well or through other recovery wells.

Solution mining commonly creates large openings below the land surface into which overlying geologic strata can collapse or subside. The collapse of the strata may partly or even completely destroy a shallow aquifer that previously had been a potential source of potable groundwater. Areas of collapse are common in the extraction of sulfur by the Frasch process, and in the solution mining of salt and potash.

CHAPTER VII

ECONOMIC CRITERIA FOR AQUIFER EXEMPTION

As previously indicated, technological factors alone probably will not preclude using any aquifer that meets the basic definition of a USDW as a drinking water source. Economic factors will also play a significant role in an aquifer exemption decision process. These considerations will involve the value of the aquifer as a drinking-water source compared with the value of the minerals, hydrocarbons, or geothermal energy associated with the aquifer, or will involve an evaluation of the cost of developing a specific aquifer in comparison with the cost of developing alternative sources of water.

The purpose of this chapter is to provide general guidelines for establishing economic criteria for aquifer exemptions. The UIC regulations (40 CFR Sec. 146.4) require economic considerations coupled with technological considerations in evaluations of aquifer exemption studies. The economic considerations most relevant include costs for the following:

- Development of aquifer as a water supply source.
- Treatment of the aquifer to drinking water standards.
- Rehabilitation of the aquifer to remove contaminants.
- Development of other available water supply sources.
- Treatment of other available water supply sources.
- Operation of existing water systems.

Cost comparisons are developed in the forms of total present worth and/or cost per thousand gallons of water produced.

The methods for determining costs for development, treatment, rehabilitation, and operation are the same for any water system in terms of capital and operational expenses. Only unit items such as water wells or water treatment plants and their associated operational costs vary depending on the type of system being evaluated. Once the capital and operational costs are established, they can be summarized in terms of total present worth and/or cost per thousand gallons for economic evaluation.

All the capital and associated annual operation and maintenance costs will vary considerably for system to system. It is impossible in this manual to detail all the various site specific possibilities. General considerations however are included (but not limited to) in the following outlines for aquifer development and water treatment costs. All or a portion of these guidelines can be selected by the evaluator for the specific system being studied. For example, to determine the cost of developing a polluted aquifer as a new water supply source, the 20 year present worth of a new well field would be combined with the 20 year present worth of the water treatment plant required. This might be compared with the 20 year present worth of operational costs of an existing water system.

Once the requirements of a system have been determined, such as population served, number of wells required, gallons per day to be treated, etc., the evaluator is ready to develop the capital and operation and maintenance costs for that system.

Groundwater Aquifer Development

A. Capital Costs

1. Groundwater rights
2. Water wells
3. Pumping stations
4. Transmission lines
5. Administration, legal, engineering, and right-of-way

B. Annual Operational and Maintenance

1. Electrical
    a. Water wells
    b. Pumping stations
2. Maintenance
    a. Parts
    b. Contract labor

Water Treatment Plant

A. Capital Costs

1. Surface water rights
2. Raw water pumping stations
3. Transmission lines
4. Water treatment plant
5. Administrative, legal, engineering, and right-of-way

B. Annual Operational and Maintenance Costs

1. Electrical

   a. Raw water intake pump

   b. Water treatment plant

2. Chemical

   a. Alum

   b. Lime

   c. Carbon

3. Maintenance

   a. Parts

   b. Contract labor

4. Personnel

<u>Cost Summary</u>

A. Total Present Worth*

1. Total Capital Cost

+ Total Annual Operation & Maintenance Costs)(Present Worth Factor)

= Total Present Worth

B. Annualized Cost Per Thousand Gallons

1. (Total Capital Cost / Present Worth Factor)

+ Total Annual Operation and Maintenance Costs

= Total Annual Cost

2. Total Annual Costs / $\left(\frac{\text{Total Gallons}}{1,000}\right)$ = Cost/1000

* Present worth factors are selected for desired interest rate and number of years from any standard present worth table.

Again, each individual case will vary according to the site specific criteria pertaining to the system being evaluated. It is the responsibility of the evaluator to obtain the necessary cost data and organize it in a logical manner. The previous outlines are general guidelines only and are not to be taken as "blueprint models" for every possible system to be evaluated.

To further illustrate the methods used to prepare a cost summary of a system, the following example has been prepared. The problem is to develop the costs involved for a city, Anytown, USA, with an existing water system to convert to a polluted drinking water aquifer that is being considered for exemption status. The existing distribution system will be used so only the costs to develop the aquifer and treat the water to drinking water standards are required. The assumptions, capital costs, operation and maintenance costs, total present worth, and cost per thousand gallons are included.

Assumptions

The proposed water system using the polluted aquifer in the contaminated region would require all new construction including water wells, water treatment plant, pumping, and piping. The finished potable water would be delivered to the customer by the existing storage and distribution system for the city. The required number of new production wells, water treatment plant sizing, and pumping would be equal to the present design and average daily flows of the existing system. The project life, once all units were operational, would be 20 years with no increase in present population or demand. This assumes the existing sources and the polluted aquifer to be adequate, long range water supplies.

The assumptions and methods used in determining these costs are as follows:

- Design Data - "Anytown, USA"

Design Flow	2,300,000 GPD
Average Daily Flow	850,000 GPD
Polluted Aquifer Depth Range	1,000-6,000 feet

- The costs represent only construction and operation and maintenance costs for the required equipment and do not include administrative, legal, staffing, or land purchases.

- The proposed systems are sized for the design flows and operated at the average daily flows of the two existing systems.

- The wells are completed to a total depth of 5500 feet with a 14" open hole from surface to 1200 feet and a 9" open hole from 1200 feet to 5500 feet. A 25 HP, 60 gpm submersible pump is set at 1100 feet inside an 8" casing landed at 1200 feet. This represents an "optimized" theoretical well, fully penetrating the polluted aquifer and is sized based on the calculated yield of the formation making up the aquifer. The formula used is (Patrick Powers, 1981):

$Q/s = 70\% \times T/[264 \log (Tt/2693\ r^2 S)] - 65.5$

where T = Transmissivity = (KB) = 176 gpd/ft

K = Hydraulic conductivity = .04 gpd/ft^2

B = 4,400 ft. formation thickness

S = 5×10^{-4} coefficient of storage for artesian aquifer

r = Radius of well = 4.5 inch = 0.375 ft.

t = Length of time well is pumped in minutes 30 days = 43,200 minutes

70% = Well efficiency

h = Drawdown = 1100 ft.

Q/s = 0.0775 gpd/ft of drawdown for a 100% efficient well

Q = $0.0775 \times 1100 \times 0.7 = 59.7$ gpm $\simeq$ 60 gpm

Cost of each well is estimated at $150,000.

- The water treatment plant provides aeration, iron removal, carbon adsorption, clarification, filtration and ranges in cost from $3.00 to $4.25/gallon capacity. Chemicals include alum, soda ash, and activated carbon.

- Pumping and piping costs assume close proximity of units and minor changes in elevation.

- All electrical costs are based on $0.06/kwh and steady state average daily flow.

- Maintenance includes parts, supplies, and contract labor only.

Capital Costs

1. Polluted Aquifer Development

30 wells @ $150,000/well	$ 4,500,000

2. Water Treatment Plant

2.3 MGD Water Plant @ $3.00/gallon	$ 6,900,000

3. Pumping Station

2.3 MGD Pumping Station L.S.	$ 50,000

4. Transmission Lines

Well System header and pipeline L.S.	$ 100,000

Annual Operation and Maintenance Costs

1. Electrical

a. Wells:

10 wells x 25 HP x .746 x 24 hrs x 365 days/yr x $0.06/kwh	$ 98,024

b. Water Treatment Plant:

35 HP x .746 x 24 hrs x 365 days/yr x $0.06/kwh	$ 13,723

c. Pump Station

$$\frac{600 \text{ GPM} \times 150' \text{Total Dynamic Head}}{3960\ (.9)\ (.7)} = 36 \text{ HP} \qquad \text{use 40 HP}$$

40 HP x .746 x 24 hrs x 365 days x $0.06/kwh	$ 15,684

2. Chemical

a. Alum

30 ppm x 0.85 MGD x 8.34 lbs/gal x 365 days x $15/100 lbs	$ 11,625

b. Soda Ash

15 ppm x 0.85 MGD x 8.34 lbs/gal x 365 days x $12/100 lbs	$ 4,657

c. Carbon

30 ppm x 0.85 MGD x 8.34 lbs/gal x 365 days x $20/100 lbs	$	15,525

3. Maintenance

a. Parts and contract labor L.S.	$	75,000

8 1/2% 20-Year Present Worth and Cost Per Thousand Summary of Anytown, USA, using the Polluted Aquifer

Item		Anytown, USA
Design Flow		2.3 mgd
Average Daily Flow		0.85 mgd
Capital Costs		
Wells		$ 4,500,000
Water Treatment Plant		$ 6,900,000
Pumping Station		$ 75,000
Pipelines		$ 200,000
	Total	$11,675,000
Annual Operation and Maintenance Costs		
Electrical		
Wells		$ 98,000
Water Treatment		$ 14,000
Pumping		$ 16,000
Chemical		$ 32,000
Maintenance		$ 75,000
	Total	$ 235,000
Present Worth		
Capital Cost		$11,675,000
O&M (9.727)		$ 2,285,845
	Total New Present Worth	$13,960,845

Cost/1000 Gallons

Capital Cost / (9.727)	$ 1,200,300
Annual O&M	$ 235,000
Total Annual Cost	$ 1,435,300
Cost per Thousand (@ 0.85 mgd)	$4.626/1,000

The answers, total present worth and cost per thousand gallons could be used by the evaluator along with technological considerations in evaluating aquifer exemption status. The principals and methods are the same whether the system being considered is the development of a polluted aquifer or water treatment for other available sources. The site specific information and the impact of the cost summaries are the responsibility of the evaluator. The more accurate the field data and unit costs are, the more reliable and useful the summaries will be for evaluating the aquifer exemption status.

As a final aid to the evaluator, a guideline checklist is provided for considerations in preparing cost summaries.

Checklist for Data Required to Prepare Cost Summaries

A. Design Criteria

1. Population served
2. Average daily flow
3. Design maximum flow
4. Depth range of polluted aquifer
5. Distance of water supply source to consumer
6. Water quality of supply
7. Type of treatment required to produce potable water
8. Firm yield of supply source
9. Long range adequacy of supply
10. Volume of aquifer to be rehabilitated

B. Capital Costs

1. Water rights
2. Water wells
3. Water treatment plants
4. Pumping stations
5. Transmission lines
6. Administration
7. Legal
8. Engineering
9. Right of way

C. Annual Operation and Maintenance Costs

1. Well field electrical
2. Water treatment electrical
3. Pumping station electrical
4. Water treatment chemical
5. Parts
6. Contract labor
7. Salaried personnel

D. Cost Summary

1. Required interest rate
2. Project life (number of years)
3. Appropriate present worth factor
4. Total present worth
5. Cost per thousand gallons

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APPENDIX

Aquifer Exemption Evaluation
Suggested Check List

A. **General Inventory Information**
[refer to EPA-UIC Permit Application Form 7520-6(2-84)]

1. Facility name, address, EPA ID number
2. Owner name and address
3. Operator/legal contact name, address and telephone
4. Ownership status
5. Standard Industrial Classification (SIC) codes best describing the nature of the business in order of priority
6. Well Status - Active, inactive, dry, abandoned (temporarily or permanently)
7. Type of Permit - Individual or Area
8. Class and Type of Well - Use same codes as required in an injection well permit application
9. Location of Well - latitude and longitude or township, range, section (For an area permit give the latitude and longitude of the approximate center of the area)

B. **Area of Review Methods**

1. Narrative description: alternative methods and procedures

    a. Fixed radius (one quarter mile)
    b. Pressure buildup method
    c. Volumetric method
    d. Modeling (if applicable)

2. Data and assumptions applied in calculation of Area of Review

    a. Injection rate
    b. Original bottom hole pressure
    c. Static water level of overlying USDW
    d. Effective thickness of injection zone
    e. Effective porosity of injection zone
    f. Horizontal and vertical permeability estimates within the proposed exempted aquifer
    g. Specific gravity of fluid in injection zone
    h. Project life

3. Computations (including references for all equations)

C. Maps of Wells/Area and Area of Review

1. Topographic Map: USGS Quadrangle sheet as base map

   a. Surface facilities, intake and discharge structures, and all hazardous waste, treatment, storage or disposal facilities
   b. Project Area
   c. Public water supply facilities

2. Topographic Map (same scale as above)

   Within the area of review the map must show:

   Class I
   a. The number, name, and location of all producing wells, injection wells, irrigation, water supply, enhanced recovery, dry holes, surface bodies of water, springs, mines (surface and subsurface)
   b. Roads, residences and faults (if known or suspected)
   c. Wells, springs, other surface water bodies, and drinking water wells located within one quarter mile of the facility

   Classes II - V
   In addition to requirements for Class I include pertinent information known to the applicant, applicable to the particular class of injection wells.

3. Surface Geologic Map

4. Structural Contour Map (on top of injection formation)

5. Geologic Cross-Sections (2 perpendicular sections)

   a. Geologic formations
   b. Structural features
   c. Shallow aquifers
   d. TDS levels for each formation
   e. Faults, fractures

6. Stratigraphic Column (by formation)

   a. Lithology
   b. Mineralogy
   c. Physical features (texture bedding)
   d. Thickness
   e. Formation hydraulic conductivity/permeability
   f. Salinity profile
   g. Geologic time scale

7. Isopach Maps (2)

   a. Confining zone
   b. Injection zone

8. Area of Review (on topographic map showing well locations)

   a. Fixed quarter mile radius
   b. Pressure buildup method
   c. Volumetric reservoir calculations
   d. Modeling output (if appropriate)

9. Maps and cross-sections showing the vertical and lateral limits of all USDW's within the area of review, and direction of water movement.

D. Corrective Action Plan and Well Data

(Data on all wells within the area of review)

1. Corrective action plan for unplugged wells
2. Tabulation of all wells penetrating zone with:

   a. Type of well (production, injection ,dry, irrigation, water supply)
   b. Well depth
   c. Status (active, inactive, plugged, abandoned)
   d. Operator/Legal Contact
   e. Date drilled (including workover dates)
   f. Construction information (cementing, casing and completion data)
   g. Injection/Perforated Interval
   h. Location
   i. Distance from injection well
   j. Plugging records
   k. Was injection above the fracture pressure of the injection zone.

E. Name and Depth of USDW's

1. Geologic names of all USDWs
2. Depth to bottom of all USDWs which may be affected by injection

F. Maps and Cross-Sections of Geologic Structure of Area

This has been detailed in Section A

G. Hydrogeology of Injection and Confining Zones

1. Hydrogeology of Injection Zone

    a. Thickness
    b. Age
    c. Lithology
    d. Mineralogy
    e. Structure (faults, fractures, cavities)
    f. Description of lateral and vertical continuity
    g. Bedding, texture
    h. Hydrologic parameters

        1) Hydraulic conductivity (permeability), vertical and horizontal
        2) Effective porosity
        3) Reservoir pressure
        4) Storage coefficient
        5) Fluid saturations
        6) Compressibility
        7) Temperature
        8) Viscosity
        9) Density

2. Hydrogeology of Confining Zone

    a. Thickness
    b. Age
    c. Lithology
    d. Mineralogy
    e. Structure (faults, fractures, cavities)
    f. Vertical and lateral extent of clay/shale layers
    g. Description of vertical and lateral continuity (eg. depositional environment, facies changes, unconformities)
    h. Hydrologic parameters

        1) Hydraulic conductivity (permeability)
        2) Porosity
        3) Fluid saturations
        4) Compressibility
        5) Poisson's Ratio

H. Operating Data

1. Average and maximum injection rates (daily) and volume
2. Average and maximum injection pressure
3. Annular fluid (type, volume, additives, pressure)
4. Source and analysis of injection fluid
5. Results of injectivity testing (if applicable)

I. 1. Formation Testing Program

a. Collection and analysis of representative formation sample
b. Description of sampling and analytical procedures
c. Direction and rate of groundwater flow
d. Salinity (TDS) profiles
e. Fluid pressure and temperature
f. Estimated fracture pressure
g. Density

2. Injection Fluid Characteristics (by individual waste streams)

a. Narrative description of individual waste streams
b. Mix ratio (ave., max., daily)
c. Constituent analyses and RCRA waste characterization
d. Cumulative analysis of commingled injectate
e. Detailed description of sampling and analytical methods
f. Temperature, pH and radiological characteristics
g. Results of compatibility studies (if applicable)
h. Density

J. Stimulation Program

1. Fracturing
2. Acidizing
3. Other

K. 1. Injection Procedures

a. Filter types and location in system
b. Injection pumps (type and capacity)
c. Tank size, capacity, and construction material

2. Surface Treatment Facilities

a. Process diagram (with descriptions of individual units)
b. Narrative process description
c. Disposal of sludge and hazardous materials
d. Effectiveness of treatment (removal efficiencies)

L. Construction Procedures

1. Total depth
2. Type completion
3. Surface

    a. Size
    b. Type
    c. Weight
    d. Setting depth
    e. Number and location of centralizers, wall scratchers, etc.

4. Intermediate casing

    a. Size
    b. Type
    c. Weight
    d. Setting depth
    e. Number and location of centralizers, wall scratchers, etc.

5. Long string casing

    a. Size
    b. Type
    c. Weight
    d. Setting depth
    e. Number and location of centralizers, wall scratchers, etc.

6. Liner or other casing

    a. Size
    b. Type
    c. Weight
    d. Setting depth

7. Logging program

    a. Surface (open) hole

        1) spontaneous potential
        2) resistivity
        3) caliper

    b. After surface casing installed

        1) cement bond, temperature or density log

c. Before installation of intermediate and long string casing

   1) spontaneous potential
   2) resistivity
   3) porosity log
   4) gamma ray log
   5) directional or inclination survey
   6) fracture finder log

d. After casing installed

   1) cement bond, temperature, density, radioactive tracer or other logs

8. Cementing Data

   a. Surface casing

      1) type cement
      2) volume
      3) cementing technique and equipment

9. Tubing

   a. Size
   b. Type
   c. Setting depth

10. Packer

   a. type
   b. setting depth

M. Construction Details

1. Engineering Drawings

   a. Well construction (downhole sketch)
   b. Well head

N. Changes in Injected Fluid

Discuss expected changes in

1. Pressure
2. Native fluid displacement
3. Direction of movement of injected fluid

O. Plans for Well Failures

Outline contingency plans to cope with all shut-ins or well failures, so as to prevent migration of fluids into any USDW.

P. Monitoring Program

1. Monitor Wells

   a. number and location
   b. frequency of sampling and testing

2. Duration of monitoring program for

   a. analysis of injected fluid
   b. injection pressure and annulus pressure
   c. flow rate
   d. cumulative volume

      1) weekly for produced fluid disposal
      2) monthly for enhanced recovery wells
      3) daily for the injection of liquid hydrocarbons and injection of fluids for withdrawal of stored hydrocarbons
      4) daily for cyclic steam operations

Q. Plugging and Abandonment Plan

1. Plugs

   a. type
   b. location

2. Cement

   a. type
   b. grade
   c. quantity

3. Narrative description of placement of method (from static equilibrium)

   a. balance method
   b. dump bailer method
   c. two plug method
   d. approved alternate method

4. Detailed cost estimate

5. Casing and tubing to be removed (size and length)

R. Necessary Resources

Evidence such as a surety bond or financial statement to verify that the resources necessary to close, plug or abandon the well are available.

S. Aquifer Exemptions

1. Does not serve as a source of drinking water
2. Cannot now and will not in the future serve as a source of drinking water
3. TDS of the aquifer and whether it is capable of supplying a public water system or not.
4. Aquifer water quality data and salinity profiles
5. Depth to proposed injection zone
6. Thickness of injection interval
7. Effective porosity and permeability in injection zone
8. Vertical separation of injection zone from overlying USDW's
9. Depth of deepest water wells in the vicinity of the proposed exempted aquifer.
10. The hydrogeology of the injection and confining intervals as listed earlier in the checklist
11. Data to demonstrate that the aquifer is expected to be mineral or hydrocarbon producing
12. Injection volumes, rates and pressures
13. Type of fluids to be injected
14. Project life of proposed facility
15. Approximate radius of migration of injected fluids within the aquifer during life of project
16. Chemistry of the native formation fluid prior to any injection
17. Rate and direction of groundwater movement
18. Distance from alternative water sources, including public water supplies
19. Current source of water supply for potential users of the proposed exempted aquifer
20. Availability and quality of alternative water supply sources.
21. Analysis of future water supply needs within the general area
22. Costs to develop the proposed exempted aquifer as a water supply source and costs to develop alternative water supplies.
23. Costs to recover and treat the groundwater to potable standards, including well construction and transportation costs.
24. Costs to develop current and probable future water supplies including construction, transportation and treatment costs.